# ENGINEERING INSTRUMENTS AND METERS

# ENGINEERING INSTRUMENTS & METERS

BY

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WITH NUMEROUS ILLUSTRATIONS

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IN ADVANCING THE SCIENCE OF MEASUREMENT

# PREFACE

Reliable measuring appliances are essential for the scientific control of industrial operations, and the study of the basic principles involved in the design of such instruments is a subject of fascinating interest. To the user of measuring instruments a knowledge of their construction and accuracy is a matter of fundamental importance, since frequently large issues depend upon their indications. Too often, when their limitations are not fully appreciated, there is a tendency to trust to the instrumental record as being absolutely exact and to regard the instrument as an infallible authority.

In the following pages the writer has attempted to give a brief review of the appliances which have been devised for the measurement of some of the fundamental quantities of mechanical science. They are all working propositions. With the majority of the machines described he has had practical acquaintance, but he has also drawn freely upon published information, and reference to the original sources will be found at the end of each chapter. Whilst no attempt has been made to form a complete bibliography of the subject, these references will enable the reader to find the detailed account of any appliance in which he is especially interested.

It is hoped that a study of this volume will enable the reader to appreciate the advantages and drawbacks of the various types of instruments for making any particular measurement, and enable him to choose the instrument best suited to his requirements, since the nature of the work in hand must be the deciding factor in the selection. The one essential characteristic of an industrial instrument is that it should be reliable and give the information sought for with reasonable ease and rapidity; time is a factor which has to be considered as much in repetition testing as in mass production.

The idea prevails in some quarters that laboratory appliances and industrial instruments belong to two totally distinct categories, and that the former are unsuited to the requirements of the works test room. But a study of modern measuring appliances proves beyond doubt the fact that no laboratory instrument is too delicate, or of a too

complicated character that it cannot be developed into a rugged instrument if the need for it occurs in the industries. Consequently the writer has occasionally introduced descriptions of instruments at present employed only in scientific work of the highest precision in the belief that the novel features embodied in such machines will ultimately be incorporated in the appliances used for routine tests.

The writer desires to acknowledge the help he has received from his brother, Ezer Griffiths, in the preparation of the work.

E. A. G.

TEDDINGTON,
*August*, 1920.

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# ENGINEERING INSTRUMENTS

## CHAPTER I

### THE MEASUREMENT OF LENGTH

THE modern practice of manufacturing interchangeable parts of machinery has given a tremendous incentive to precision measurements.

To ensure a good working fit in moving parts as well as thorough interchangeability requires strict accuracy of dimensions in the work which is only possible by the use of gauges in the quantity production of component parts.

For the construction and verification of such gauges a very high degree of precision and refinement of measurement is necessary. Hence machines and appliances for measuring to one hundred-thousandth part of an inch are included in the equipment of the modern tool room.

The pioneers in the development of this branch of engineering were Whitworth in England, and Pratt and Whitney in America; the machines they devised are identical in principle with those in use at the present day. Before entering into a description of these appliances it is desirable to review briefly the fundamental basis of our system of length measurements.

#### PRIMARY LENGTH STANDARDS

*British Standard—the Yard.*—The origin of the British yard is the length of the arm of King Henry the First, and that of the standard inch "three good barley corns, round and dry, placed end to end."[1]

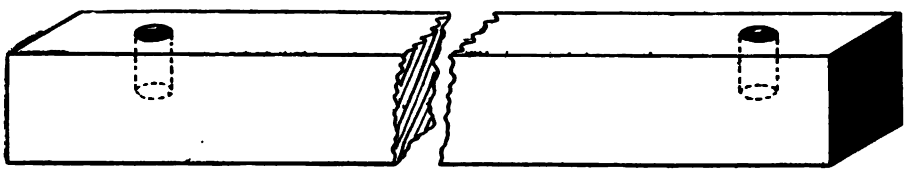
The fact that such standards were lacking in accuracy and uniformity seems to have occurred to our forefathers at a very early date, for we find in the records that Richard I ordered that the standard measures of length should be made of iron, and that standards should be kept by the sheriffs and magistrates of towns.

In 1340 a royal edict was published ordering standard weights and measures to be made of brass and sent to every city and town in the

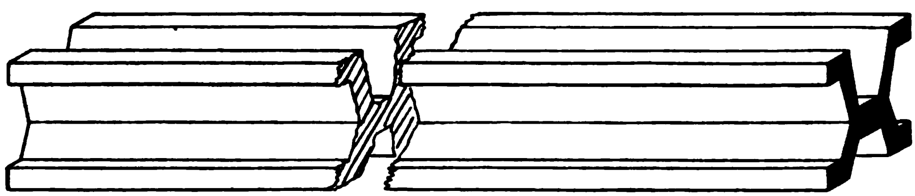
[1] Statute of Edward II, 1324.

kingdom. These old standards have been lost or destroyed in the course of time, and the earliest surviving standards of length are those of Henry VII (about 1490) and Elizabeth (about 1588).

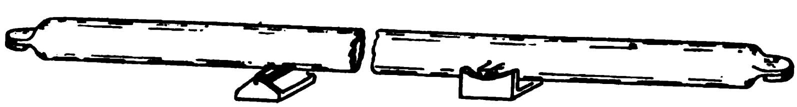
It is interesting to note that the present-day standard, the Imperial yard, is identical within the two-hundredth part of an inch with the yard of Henry VII. The Elizabethan standard was broken and repaired by means of a dovetail joint at some period of its career, but it still continued to serve as the fundamental standard down to 1824.



IMPERIAL STANDARD YARD (BRONZE)



PLATINUM IRIDIUM COPY OF IMPERIAL YARD, 'TRESCA' SECTION.



SILICA METRE
(GRADUATIONS ON UNDER FACE OF FLAT ENDS.)

FIG. I.

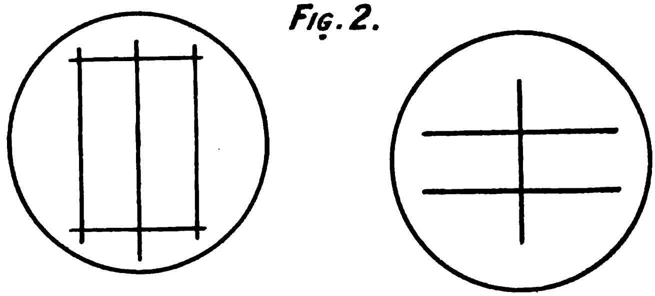
In 1843 a definite advance was made by the establishment of the Imperial yard, which was legalized in 1855. The Imperial standard yard is a solid square bar of Baily's metal, a bronze alloy composed of 16 parts copper, 2½ parts tin, and 1 part zinc (Fig. 1).

The bar is 1 square inch in cross-section and 38 inches long. At positions 1 inch from each end cylindrical holes, ½ inch in diameter, are bored for a depth of half an inch. In the centre of the base of these depressions a gold plug is inserted, the exposed surface of which, lying in the neutral plane, has been planed true. The defining mark is engraved

approximately at the centre of this gold circular surface, actually five lines are engraved, two parallel to the length of the bar and three transversely, the appearance being as shown in the diagram, Fig. 2. It is the central one of the three transverse lines (vertical in figure) which is the defining mark, and the distance between this mark and the corresponding mark in the depression at the other end is the Imperial yard.

Unfortunately alloys, and particularly copper alloys, are liable to alter with time, and it has been discovered by making intercomparisons of the bronze Imperial standard yard and its official copies that variations have arisen in the length of the different bars. In two cases the relative variation in ten years was nearly four parts in a million. Hence copper alloys are now regarded as unsuitable for the construction of primary

FIG. 2.



REFERENCE LINES ON STANDARDS.

standards owing to the changes of length due to some molecular rearrangement slowly taking place.

In 1902 an official copy of the Imperial standard yard was constructed in platinum iridium (90 per cent. platinum with 10 per cent. iridium). This was made of X-shaped or "Tresca" section, with one transverse line engraved at each end on the horizontal transverse portion of the bar, which contains the centre of the section. The reason for placing the graduations at the centre of the depth of the bar was to reduce errors which might arise from flexure of the bar itself.

The importance of this point was first realised by Captain Kater, who published an account of an investigation on the subject in the *Philosophical Transactions* of the Royal Society in 1830. The magnitude of the effect depends, of course, on the method of supporting the bar, which in consequence has to be carefully specified. A mathematical treatment of the subject was given by Sir G. Airy, who gave the formula for determining the distance between the supports for any standard bar in order to minimise the effect of flexure.

It is :—

$$\text{Distance between successive supports} = \frac{\text{Length}}{\sqrt{n^2-1}}$$

where "n" is the number of point supports.[1] Generally a two-point support is adopted, since it removes the uncertainty that exists as to the pressure distribution when a bar not ideally straight rests on a series of supports not ideally coplaner.

When a bar is supported on two points, not at its extreme ends, there will be two points of inflexion in the bar between the supports, and the bar will be concave on the upper side in the centre, and concave on the under side at its ends. According to Airy's formula, to obtain the maximum projected horizontal length the distance apart of the supports must be

$$\frac{l}{\sqrt{3}} = 0{\cdot}5773\, l$$

where $l$ is the length of the bar. Hence for a bar 38 inches long the distance between the supports should be 22 inches.

*French Standard—the Metre.*—Talleyrand, in 1790, proposed to the Assembly of France that a commission be appointed to consult with a similar commission from the English Government to consider the subject of a uniform system of metrology. The invitation was not accepted by the British Government of that day. The International Commission decided to adopt as unit the ten-millionth part of a quadrant of the earth's meridian, and the first practical unit on this basis was constructed by Borda in 1795, which is now known as the *Mètre des Archives.*

*Mètre des Archives.*—This was made of platinum, which does not tarnish, and being a pure metal is unlikely to change with time. It has, however, the serious defect of being soft and exceedingly expensive.

*International Prototype Metre.*—To overcome the objection of the softness of platinum an alloy of platinum, 10 per cent. iridium, was used in the construction of the International Prototype Metre in 1887.

Great care was taken in refining and artificially ageing the material so as to reduce as much as possible the inherent defects of alloys. The metre was of Tresca cross-section (Fig. 2.) Prototypes of this metre are in the possession of all the principal nations.

## Secondary Standards

The above described are the ultimate standards, and are only referred to on rare occasions when extreme precautions are taken to safeguard

[1] In the Imperial bronze yard, Fig. 1, the number of supports is eight, at distances apart of 4½ inches.

the standard from accidental damage or disturbance which might affect its permanency. For standardising work in institutions such as the National Physical Laboratory, a nickel copy of the International metre is employed. This is of H section, with the graduations on the horizontal arm. Comparison with the French standard has shown an increase of length in the nickel metre of only one part in ten million in ten years. The metal has the advantages of hardness, non-tarnishing, takes a high polish, and is about as elastic as steel.

### Fused Silica as a Material for Primary Standards

An interesting experiment was tried at the National Physical Laboratory some time ago in connection with the construction of new length standards. Platinum alloys are too costly, and pure nickel has a large coefficient of thermal expansion which is objectionable in practical work. Fused silica has an exceedingly small coefficient of expansion and being a simple chemical compound $SiO_2$ should not be liable to change with time. In appearance the material closely resembles glass, and its glass-like brittleness is its great drawback. Experiment has shown that it has a remarkably small hysteresis after annealing. Fused silica is most readily obtained in the form of tubing, consequently the design was such as to utilise the material in this form. Fig. 1 illustrates the metre as constructed in 1910. It consists of a transparent silica tube about 2 cms. in diameter and a metre in length. The tube merges at each end into a clear, transparent horizontal slab of silica for taking the reference lines. A silica knife-edged trunnion is fused into the rod at one of the correct points of support. The other point of support is indicated by a ring which has been etched round the tube. The reference lines are cut in a film of platinum deposited on the silica. The graduations are cut completely through the film and the lines viewed from above through the slabs. These end slabs took the form of semi-circular discs which were made of specially clear silica, free from bubbles, the upper and lower surfaces being parallel and both optically polished.

It is too early yet to decide whether this type of standard will meet requirements.

### Working Standards of Length

None of the materials already described are suitable for use in the construction of tool-room standards of length, and until recently steel was the material in general use. This has the disadvantages of liability to rust and of having a relatively high coefficient of expansion. The im-

portance of the question of the temperature coefficient of the standard is frequently overlooked in engineering work, but in ordnance survey work it was, in the past, a most troublesome factor to correct for. For example, a steel wire 1 kilometre long would expand in passing from 0° to 22°C. by 22 mm. Invar wire[1] under the same conditions would contract by an amount less than 0·4 mm.

Hence the discovery by Guillaume of the small expansion by heat of the nickel-steel alloy known as invar, and the employment of that alloy in the form of wires for the measurement of geodetic base lines, has revolutionised survey practice in that operation. It is stated that with the now obsolete apparatus belonging to the survey of India, base-lines could only be measured at a very slow rate, viz. about 500 feet per day, whereas a skilled party with modern invar wire apparatus has measured as much as five miles in the same time and with a higher accuracy.

In this connection it is of interest to compare the coefficients of expansion of the materials hitherto employed for length standards.

TABLE I

| Material. | Density. | Coefficient of Linear Expansion per cent. | Used for. |
|---|---|---|---|
| Bronze, Baily's metal 32 Cu., 5 Sn., 2Zn. | 8·7 | $17{\cdot}7 \times 10^{-6}$ | British Imperial Standard Yard. |
| Platinum . . . | 21·5 | 8·9 | Mètre des Archives |
| Platinum Iridium 90 Pt., 10 Ir. | 21·6 | 8·7 | International Prototype Metre |
| Nickel . . . | 8·9 | 12·8 | N.P.L. Standard |
| Fused silica . . | | 0·42 | |
| Nickel Steel (43% Nickel) | c 8·2 | 8·0 | Primary master standard of Japan and Russia |
| Steel . . . | c 7·8 | c 11 | Generally used for steel rules. |

## NICKEL STEELS

"Invar" is the trade name of a nickel steel containing 36 per cent. of nickel, and its distinguishing feature is an abnormally low coefficient of expansion. This property, combined with the fact that the alloy possesses the usual characteristics of steel, has made this material of the utmost practical utility for the construction of secondary length standards, pendulum rods, and the balance wheels of watches. Its discovery was the culmination of a laborious and accurate scientific investigation following

[1] Coefficient of expansion of $(+0{\cdot}028-0{\cdot}00232\,t)10^{-6}$ per degree.

on the clue of a chance observation of a bar possessing an unusually large coefficient of expansion.

In 1895 Benoit, then director of the International Bureau of Standards and Weights, Sèvres near Paris, in the course of calibrating a length standard of steel containing some 22 per cent. nickel and 3 per cent. chromium, discovered that the linear coefficient of thermal expansion at ordinary temperatures was more than $18 \times 10^{-6}$ per degree C., or about as great as that of average bronze—that is to say, considerably greater than that of either iron or nickel.

Somewhat over a year later Guillaume, of the same institution, found the expansion of a bar of 30 per cent. nickel steel to be about one-third less than that of platinum, which has a coefficient of only $9 \times 10^{-6}$. In the hope of obtaining alloys of very small expansivity by increasing the proportion of nickel Guillaume, in co-operation with the Société de Commentry, Fourchambault, carried out an elaborate investigation of nickel steel of varying composition. The result was the discovery of alloys having coefficients of linear expansion at ordinary temperatures ranging from a small negative value ($-0{\cdot}5 \times 10^{-6}$) to a rather large positive value of about ($20 \times 10^{-6}$). The linear dimensions of the alloy containing about 36 per cent. nickel along with small amounts of manganese, silicon, and chromium, in all about 1 per cent. were found to remain almost invariable with ordinary atmospheric changes of temperature. This alloy is now well known under the name of invar.

In practice invar as obtained commercially has a coefficient of expansion varying from $-0{\cdot}3 \times 10^{-6}$ to $+2{\cdot}5 \times 10^{-6}$, the smallness of the coefficient being the criterion of the quality. Invar possesses the further advantages over steel that it does not readily rust and it will take a high polish. On the other hand, it is not a permanent alloy, and it is impossible to ensure a specified coefficient of expansion, since a very slight variation in the composition is sufficient to produce a considerable alteration in the expansibility. It is, in consequence, very important in the case of a long measure, such as a tape, to look for the effects of local heterogeneity and not assume the expansion coefficient derived from a short sample.

On account of the instability of invar the modern tendency is to use nickel steel containing 43 per cent. of nickel for standards, which has a temperature coefficient nearly that of platinum ($8 \times 10^{-6}$). In this alloy both secular change and thermal hysteresis are extremely small. The variation of the coefficient of expansion with the nickel content of the steel is shown in Table II and Fig. 3.

## TABLE II

EXPANSION OF NICKEL STEELS—MEAN COEFFICIENTS OF LINEAR EXPANSION BETWEEN 0° AND t° C; APPLICABLE BETWEEN 0° AND 38° (GUILLAUME)

| Per cent Ni. | Mean Coefficients of Linear Expansion $\times 10^6$. | Per cent Ni. | Mean Coefficients of Linear Expansion $\times 10^6$. |
|---|---|---|---|
| 0 | 10·354+0·00523 t | 44·4 | 8·508—0·00251 t |
| 5·0 | 10·529+0·00580 t | 48·7 | 9·901—0·00067 t |
| 19·0 | 11·427+0·00362 t | 50·7 | 9·824+0·00243 t |
| 26·2 | 13·103+0·02123 t | 53·2 | 10·045+0·00031 t |
| 27·9 | 11·288+0·02889 t | 70·3 | 11·890+0·00387 t |
| 28·7 | 10·387+0·03004 t | 100·0 | 12·661+0·00550 t |
| 30·4 | 4·570+0·01194 t | 12·2+1 Cr | 11·714+0·00508 t |
| 31·4 | 3·395+0·00885 t | 16·8+1 Cr | 11·436+0·00170 t |
| 34·6 | 1·373+0·00237 t | 16·2+2·5 Cr | 19·496+0·00432 t |
| 35·6 | 0·877+0·00127 t | 21·3+3 Cr | 18·180+0·00426 t |
| 37·3 | 3·457—0·00647 t | 34·8+1·5 Cr | 3·580—0·00132 t |
| 39·4 | 5·357—0·00448 t | 35·7+1·7 Cr | 3·373+0·00165 t |
| 43·6 | 7·992—0·00273 t | 36·4+0·9 Cr | 4·433—0·00392 t |

The data describe alloys cooled in the air after a simple hot forging. In addition to the nickel they contain small portions of manganese, silicon, and carbon, amounting in all to about 1 per cent. Guillaume states that these additions are necessary to render the alloy workable; in particular about a half per cent. of manganese is essential. Unfortunately they also produce an appreciable increase in the coefficient of expansion, so it is necessary to reduce them to a minimum and also subject the alloys to a special thermal and mechanical treatment.

In Fig. 3 the straight line FN, which joins the expansivity of iron with that of nickel, would represent the results to which the law of mixtures would lead if it were applicable, and the anomalous behaviour of these alloys is most remarkable.

Fig. 4 shows variation in the coefficient $b$ of the formula $a+bt$ for the coefficient of expansion of these alloys. The small circles in Figs. 3 and 4 show results obtained with alloys containing an abnormally large proportion of manganese, the percentage of which is indicated near each circle. The crosses refer to alloys containing chromium.

Fig. 5 illustrates this point more clearly. With the normal quantities of carbon and manganese present it is difficult to reduce the coefficient below 1·2 or even 1·5-millionths per degree centigrade, although by the

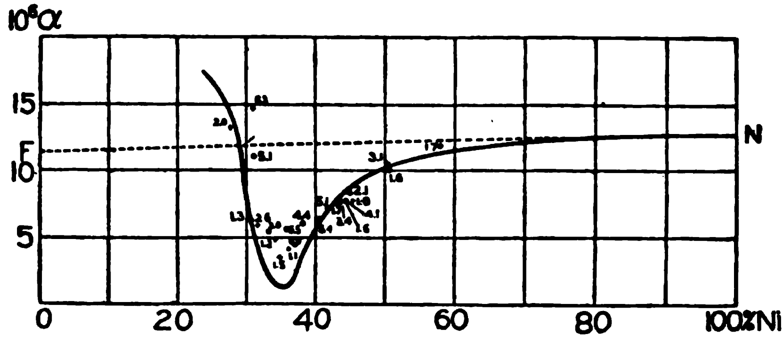



FIG. 3.—*True coefficients of linear expansion at 20° C of nickel steels.* (*Guillaume*)

Curve, normal alloys; o, alloys containing the designated per cent of manganese; +, alloys containing chromium

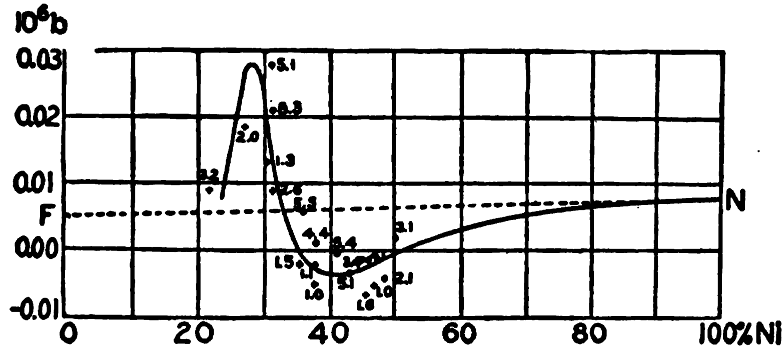



FIG. 4.—*Values of the quadratic coefficient in the formulas for the linear expansivity of nickel steels.* (*Guillaume*)

Curve, normal alloys; o, alloys rich in manganese; +, alloys rich in chromium

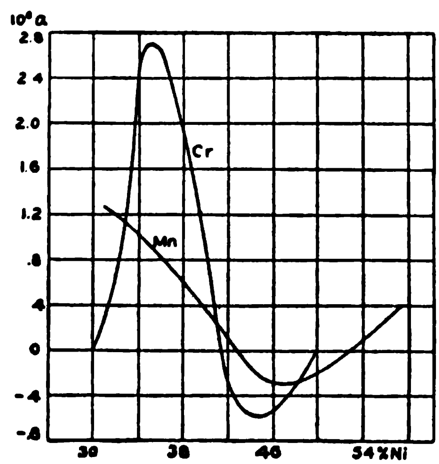



FIG. 5.—*Effect upon the linear expansivity of nickel steels produced by adding 1 per cent manganese or chromium.* (*Guillaume*)

exercise of great care in carrying out the requisite metallurgical treatment it has been possible to produce alloys with a negative value for the coefficient of expansion between 0° and 38° C given by the expression $(-0{\cdot}552+0{\cdot}00377\ t)\ 10^{-6}$.

It should be noted that the above coefficients are only applicable to a limited range of temperature, and the relatively large variation in the coefficient for various temperature ranges is illustrated by the data in Table.

## TABLE III

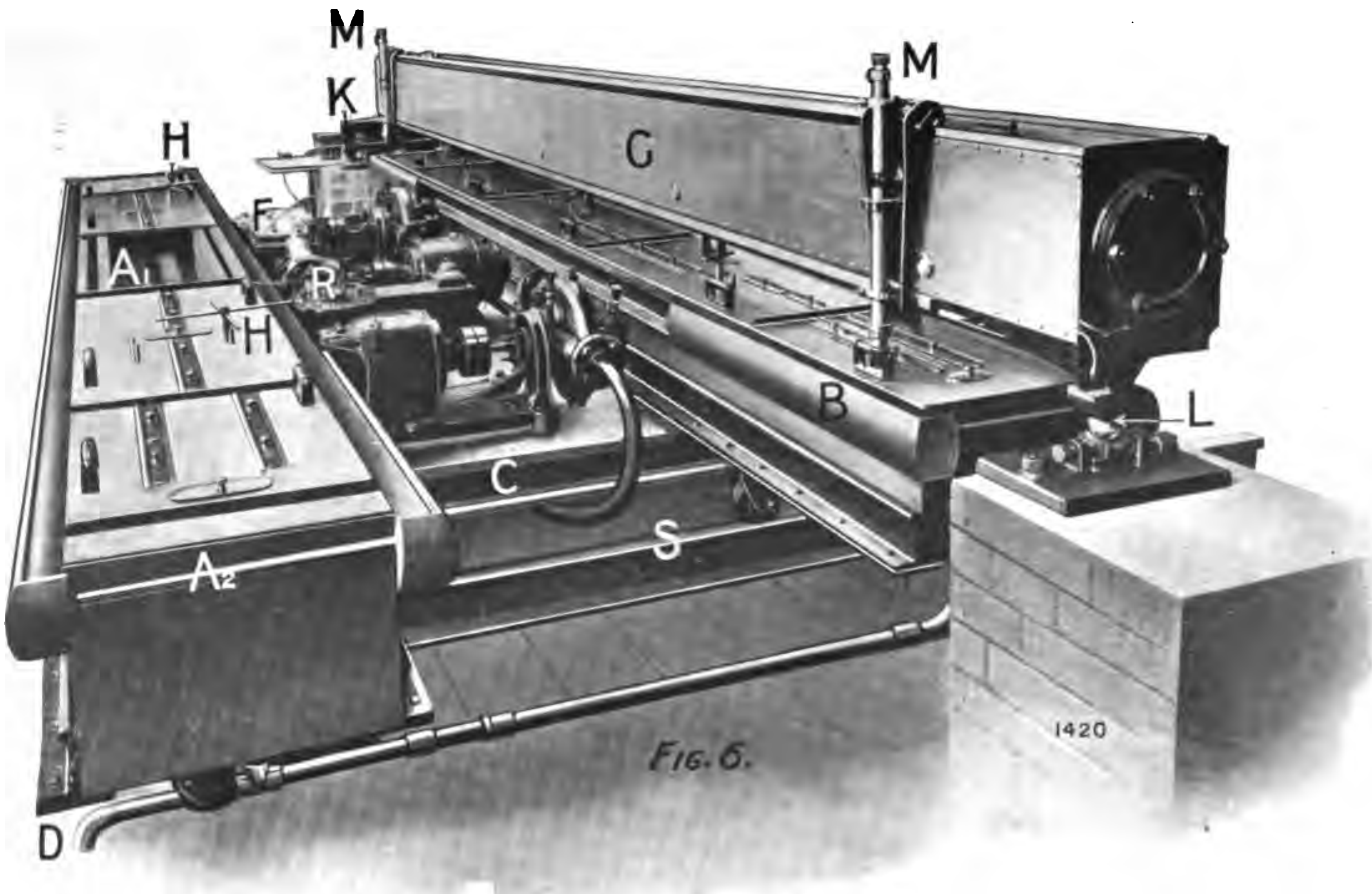
EXPANSION OF NICKEL STEELS—TRUE COEFFICIENTS OF LINEAR EXPANSION AT t° C (GUILLAUME)

| Per cent Ni. | Limits of Application. | True Coefficients of Linear Expansion × $10^6$. |
|---|---|---|
| | Degrees. | |
| 30·4 . . . . . . | 0–110 | 4·570+0·0235 (t–0) |
| | 110–164 | 7·15 +0·104 (t–110) |
| | 164–220 | 12·60 +0·008 (t–164) |
| 31·4 . . . . . . | 0–122 | 3·395+0·0150 (t–0) |
| | 122–182 | 5·25 +0·128 (t–122) |
| | 182–220 | 13·00 +0·036 (t–182) |
| 34·6 . . . . . . | 0–142 | 1·373+0·0047 (t–0) |
| | 142–220 | 2·05 +0·065 (t–14) |
| 37·3 . . . . . . | 0–150 | 3·457—0·0072 (t–0) |
| | 150–220 | 2·37 +0·011 (t–150) |

### COMPARATORS

To compare the length of copy with a standard requires elaborate appliances if an accuracy of better than one part in a hundred thousand is aimed at. Up to the year 1798 all transfers of the Standard yard were effected by the use of a beam compass—a method which does not lend itself to high accuracy. Troughton at this time introduced optical instruments for the intercomparisons, and this step marked a great advance in the progress of precision metrology. A modern type of comparator is illustrated in Figs. 6 and 7. This piece of apparatus was constructed in 1915 by the Cambridge Scientific Instrument Co., for the Indian Ordnance Survey. The essential features of the apparatus are indicated in the sketch (Fig. 7), while Fig. 6 gives a general view of the complete apparatus.

This comparator is designed for the standardisation of bars of any length up to four metres. The microscopes *M M* are bolted on to a hollow cast-iron girder G. This girder is filled with water, which by convection,


M
K
H
F
A1
R
H
G
M
B
L
C
S
A2
D
1420
FIG. 6.

and by reason of its high specific heat, tends to maintain the temperature of the girder uniform and constant throughout its length. The girder is supported geometrically, one end being mounted on two steel balls, one of which rests between cones and the other between parallel plates. The other end is supported on a 75 mm. steel ball $L$ rolling between V's parallel to the girder so that any temperature changes in the length of the girder may be taken up without putting any strain on the girder. The scales under test are immersed in tanks of water which are carried on a large travelling carriage $C$. Three pumps are also carried on this same carriage for circulating the water in the three separate tanks. The

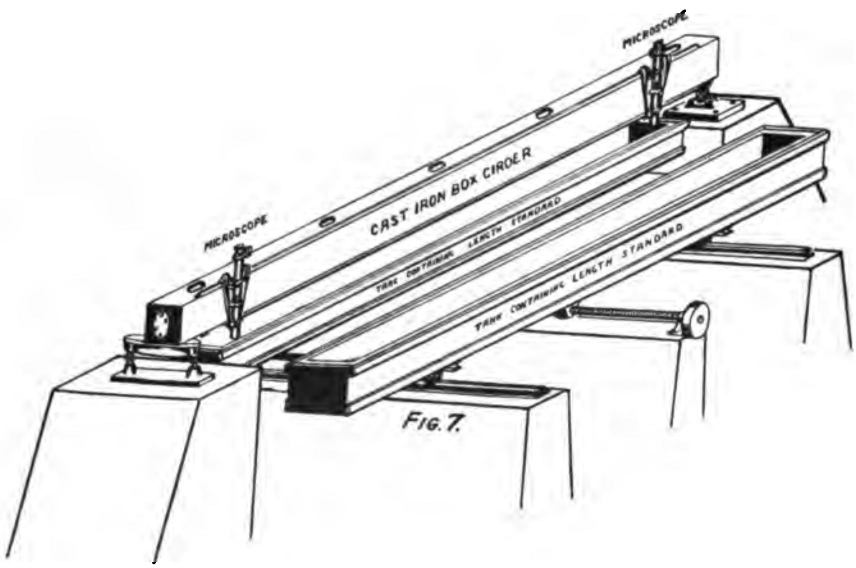



FIG. 7.

tank marked $A_1A_2$ is a double tank, that is to say, there is an inner tank $A_1$ in which the bars are placed, and this is surrounded by an outer tank $A_2$ with a separate water circulation, which acts as a jacket. Consequently the temperature of the inner tank can be maintained constant by conduction from the outer tank at any required value to one-hundredth of a degree Centigrade, when the water in the outer tank or jacket is heated and controlled as explained below. The third tank $B$ is fixed to the carriage on the other side of the three pumps. This tank always remains approximately at the air temperature and is placed well away from the double tank, so that when the latter is heated it will not cause changes in the temperature of the single tank. The inner tank $A_1$ is arranged to carry two standard scales side by side of any length up to

four metres each. The tank *B* is arranged to take only one scale. In all cases the scales are supported at their Airy points on subsidiary girders, which in turn rest on adjusting tables in the tanks. The adjustments to these tables enable both ends of the standard scale to be brought into focus under the microscopes; also that the scale can be traversed in the tank parallel to the microscope girder, and can be adjusted to be parallel to this girder. These adjustments are made by gearing from outside the tanks. Four adjustments are therefore provided on each of the three girders on which the standard scales may be placed. The whole of the carriage *C* supporting the pumps and the tanks can be traversed sideways by means of an electric motor, so that any scale in either of the tanks may be brought under the microscopes as desired.

In order to raise and control the temperature of the outer tank $A_2$, a heating vessel and a thermostat are included in the water circuit of this tank. The heating vessel contains a number of electric heating coils. The electric current in these coils is controlled by a sensitive mercury thermostat *R* acting through a relay *F*. The temperature of the water in the two tanks is measured by mercury thermometers which are read by microscopes suitably provided with right-angled prisms so that readings can be obtained when either tank is below the main microscope girder.

Experience has shown that the temperature of the inner tank can be maintained constant to 0·01° C over many hours.

If two bars are brought in succession under the microscopes, comparative readings can be made, which will allow of the length of the one being deducted in terms of that of the other. The provision of two tanks, in one of which the temperature may be regulated as desired, makes it possible to carry out a series of comparisons between two bars, one of which is maintained at a constant temperature for the whole duration of the observations, while the other is brought to a different temperature for each comparison of the series. Utilising the length of the one bar under constant temperature as a datum, the length of the second bar at varied temperatures can be determined and the characteristics concerning its thermal expansion investigated.

It might be remarked that the data concerning the expansion of nickel steels, previously described, were obtained by the above procedure. In the French comparator the microscopes are fixed on two separate pieces of masonry. When it is desired to compare two bars they are placed in the same bath so as to ensure equality of temperature. In the C.S.I. comparator each comparing microscope has a tube of invar 20

inches long, fitted with an objective of 120 mm. focal length, for a front working distance of 160 mm., and an image distance of 480 mm. from objective to the micrometer plate, the aperture being 23·5 mm., for use in the ordinary way, and with an alternative for use immersed in water. Each tube has two oculars of focal length 30 mm. and 50 mm. respectively, producing a magnification of the object of 15 and 25 respectively. It was found by observation on a graduated scale of invar that the object-glass is capable of resolving lines ruled 100 to the millimetre. Each microscope is fitted with a micrometer with a screw of 0·3 mm. pitch, threaded for a length of 6·5 mm. The female screw has an effective length of 5 mm. The drum is graduated to hundredths, the value of one revolution of the screw being about 0·1 mm. on the object. The micrometer lines are ruled on a glass diaphragm 10 mm. in diameter, as shown in Fig. 8. The apparatus was designed by a committee consisting of Sir David Gill, Sir Richard Glazebrook, Mr. Horace Darwin, and MM. Benoit and Guillaume.

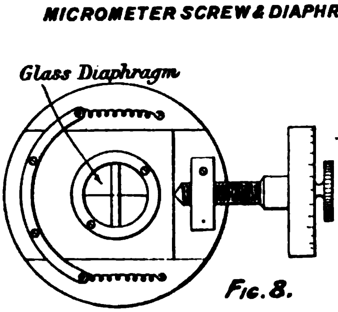



Fig. 8.

### Measuring Machines for Tool Room Use

When Sir Joseph Whitworth began to develop precision machines and tools he was confronted with the serious practical difficulty of transferring dimensions from an engraved scale to the machine part and vice versa. Engraved scales are well adapted for use as primary standards of length : here economy of time and facility of comparison are of secondary importance to high precision and absolute accuracy. In engineering practice it is essential to be able to make measurements with rapidity and reasonable ease, and with this object in view Whitworth originated the present system of end measurements.

One of Whitworth's measuring machines is illustrated in Fig. 9. It is practically a very large micrometer. The machine has a cast iron bed and two headstocks, resembling the loose headstocks of a lathe. One headstock is fixed, while the other is movable along the bed by a quick-pitched lead-screw, and its centre, or measuring end, is adjustable by a screw within the headstock. The fixed headstock has a measuring screw of 20 threads to the inch, and to this screw is attached a wheel whose circumference is divided into 500 divisions. So that one division

of the latter represents 0·0001 inch in end movement of the spindle. In using the machine it is usual to set the heads by placing between them a standard gauge as near the required dimensions as is available, and then to fix the final position of the measuring faces by moving one end through the required difference by means of the divisions on the wheel.

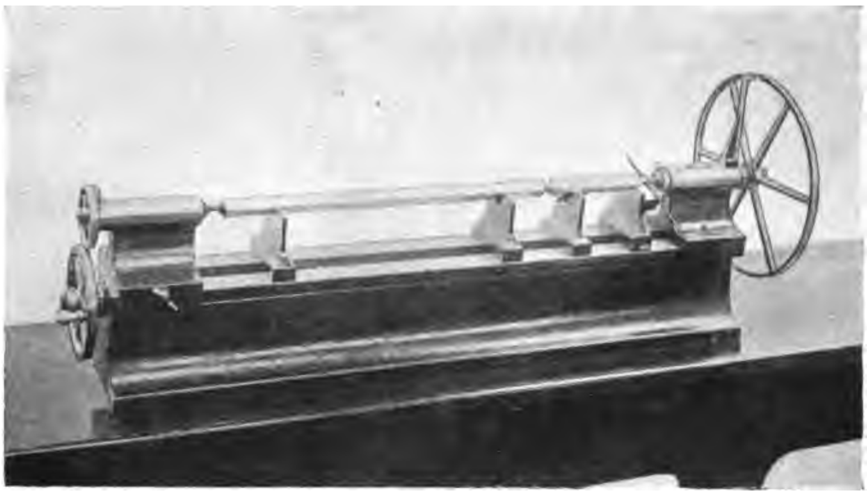


FIG. 9.

The usual type of standard gauge length is shown in Fig. 10. The steel rod has its ends rounded into spherical forms, the radius of the sphere being half the length of the rod. By this means errors due to axis of the rod not being perpendicular to the faces of the headstock are eliminated. The central part of the rod is encased in ebonite to minimise temperature changes whilst handling.

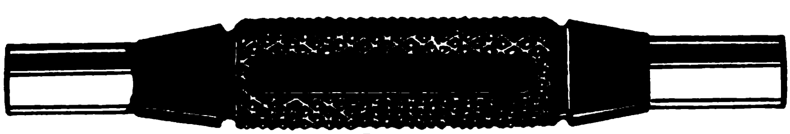


FIG. 10.

Since the year 1871, when Whitworth introduced this type of measuring machine, many improvements have been effected, notably by Pratt and Whitney in America, and the Newall Engineering Company in this country. A general view of the standard types of machines manufactured by the latter firm are shown in Figs. 11, 12, and 13. These machines are made to read to one hundred-thousandth of an inch on the British

system, or one ten-thousandth of a millimetre if graduated on the metric system.

*The Measuring Screw* bears a thread of buttress form cut specially deep to provide ample wearing surface, and has a range of 1 inch, or 20

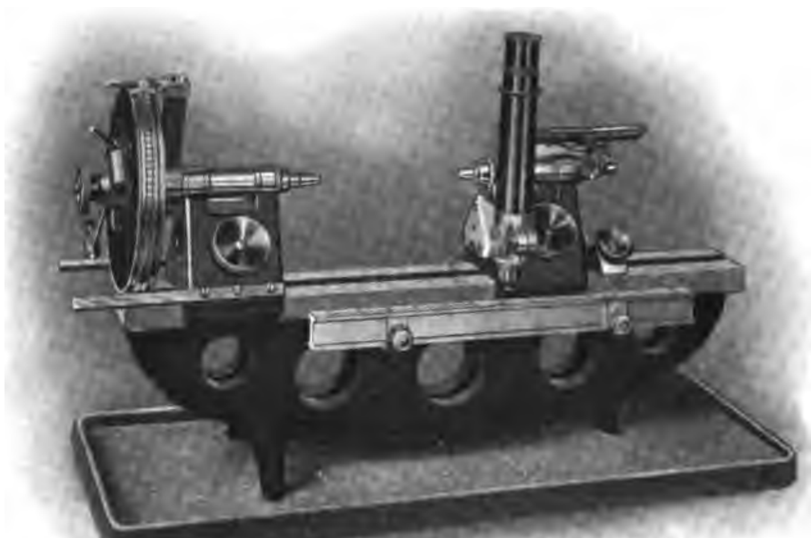


FIG. 11.

millimetres, according as it is intended for an English or a metric machine respectively. The threaded portions of the screw and its nut are equal, of not less than three times the length of range stated above, and, wear

FIG. 12.

being even, accuracy in pitch is maintained. Only a minimum amount of wear takes place on the effective portions of the thread, as the screw is supported on its plain cylindrical parts at front and rear in hardened

steel bearings, which relieve the threaded part from weight and maintain the axes of screw and nut identical and invariable.

A spring device is provided by which a constant pressure is maintained between the screw and the nut. This keeps the effective faces of the nut and screw in contact, and abolishes backlash. The importance

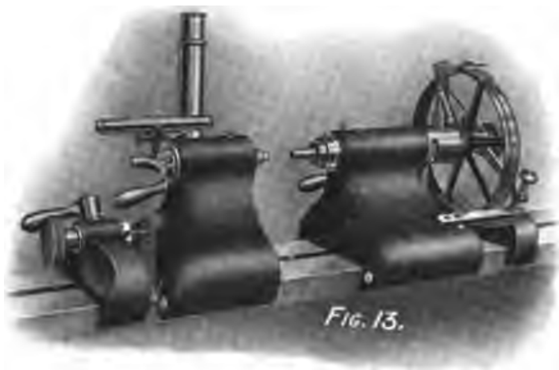


FIG. 13.

of this feature will be appreciated from the fact that oils of different viscosity used for lubricating the screw have varying effects upon the readings, and further, that a positive adjustment on such a delicate screw materially alters the pitch.

For the rapid movement of the measuring screw there is a knurled nut on the end of the spindle: this is used until a sufficient movement has been applied through the piece being measured to bring the indicator into motion. For sensitive movement a fine adjustment screw, carried on an arm, is clamped to the measuring wheel at any point by an eccentric, and this screw, thrusting against the front horizontal bar, gives the slow motion necessary.

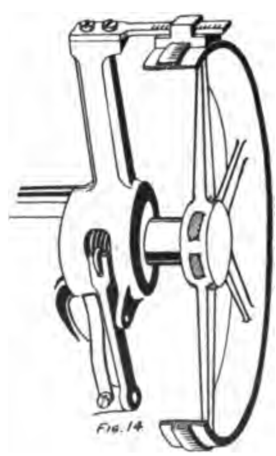


FIG. 14

*Compensator.*—In general, accuracy in pitch greater than one-ten-thousandth of an inch, if obtained, is quite accidental, for, while a screw may appear to be absolutely correct at one length, it is practically impossible to secure consistency in the same length when measured at different points in the length and helix of the screw. For this unavoidable productive error—minute as it may be—in the pitch of the measuring screw, a method of compensating is provided by an unique device shown in Fig. 14.

It is said that by this means it is possible to make the readings of the measuring screws so near to absolute accuracy that it would be extremely difficult, if not quite impossible, by any method known, to detect error at any point in their length. A secondary screw of the same pitch as the measuring screw is cut on the rear end of the spindle: undulations made on the crest of this thread impart, through a lever, carrying a roller, to the zero line on the vernier, borne on the horizontal scale which is supported on the vertical arm, forward or backward movement at any point and as may be required to compensate for the ascertained inaccuracies in pitch of the measuring screw.

*The Tailstock* carries the anvil, operating the indicator, and, in machines so fitted, the microscope for setting to the rule. It is moved bodily when setting to an End Rod, or to the rule, to obtain sizes greater than are provided by the range of the measuring screws. In machines fitted with rule and microscope an arrangement for fine adjustment is attached to the tailstock by means of which the necessary delicate movement is obtained for setting the microscope to the graduated line on the rule.

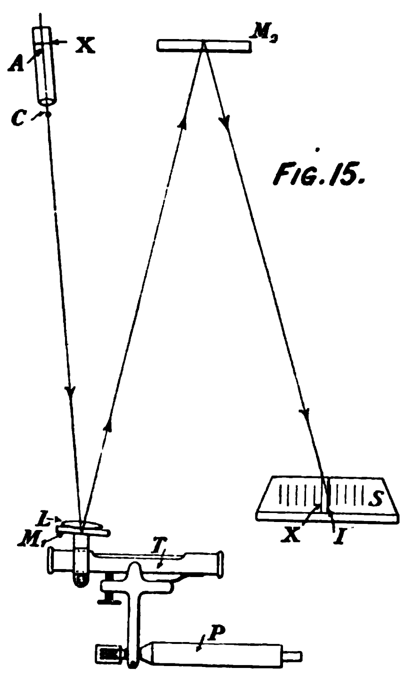



FIG. 15.

*The Indicator.*—An interesting feature of the machine is the application of a spirit level to indicate when contact is made with the specimen to be measured. A magnification of 4000 times the movement of the anvil is capable of detection. This device eliminates the possibility of personal error. A defect of the "tilting level" type of indicator for rapid work is the viscosity of the liquid in the level tube. In testing the diameter of cylinders by rotating while held between the faces it is found that the bubble is very sluggish in indicating the slight variations in diameter of the cylinder under-test, or is apt to overshoot the mark with rapid movement. To overcome this difficulty the optical lever illustrated in Fig. 15 is used at the National Physical Laboratory.

The level tube $T$ is tilted through the action of a level by the displacement of the plunger $P$ of the measuring machine. A small plate-glass

mirror $M_1$ is fixed to $T$, and a convex long-focus lens $L$ is cemented to the upper surface of the mirror. Above the machine a wall bracket holds the Nernst lamp $A$ which is provided with a condensing lens. The light from this lamp falls on a fine cross-wire $C$ and passes through the lens $L$ on to the mirror $M_1$, which reflects an image of the wire up to a second mirror $M_2$, also attached to the wall, and from this latter mirror it is finally reflected on to the horizontal divided screen $S$, placed behind the machine.

The lens $L$ is required to give a distinct image $I$ of the cross-wire on the screen, this screen being graduated with a scale of which the zero is marked $X$ on the diagram. With the arrangement adopted a movement of 0·35 inch on the screen is produced by a displacement of the plunger $P$ amounting to 0·00001 inch, so that a total magnification of 3500 is obtained by the aid of the lever carrying the level tube and the optical system. Thus the roundness and parallelism of a cylinder can readily be measured within 0·00001 inch, and as the indicator is quite dead-beat, the operations can be performed at a much quicker rate than formerly.

## GAUGES

The reader, unless he has had acquaintance with gauge making, may naturally wonder why such extreme accuracy of measurement is necessary for engineering work. The reason will be seen on consideration of the modern system of the manufacture of interchangeable parts on a quantity basis. In this system the various parts of a machine must be capable of being assembled without any fitting and adjustment of the components. Take, for example, the manufacture of a number of spindles and bearings. If a clearance of but one-thousandth part of an inch is permissible between the two parts in operation, then the tolerance permissible on the parts must be only a few ten-thousandths of an inch. This result is achieved in practice by the employment of fixed gauges. For each piece of work a fixed gauge is made comprising two sizes, one smaller and one larger, of which the former, termed the "minimum," represents almost exactly the smallest size that the piece can be made to, and the latter, termed the "maximum," the largest size that the piece can have without violating the condition of interchangeability or the function of the parts. The difference between these two limits is termed the "tolerance," and the value of this tolerance depends upon the particular class of work. By this means it is possible to produce an article much cheaper and quicker than would be the case if the utmost accuracy to a given size was attempted.

Figure 16 illustrates a typical fixed gauge. It is obvious that the gauges must be very accurate to the specified dimensions, otherwise not only will the tolerances be affected but also, if the errors of the two sets of gauges for the respective interchangeable parts happened to be in opposite direction and of such magnitude, the parts might not fit together at all and consequently the sole object of limit gauging would be defeated. When only a small number of gauges are in use they are usually set and

FIG. 16.

checked in the tool room by means of measuring machines or Johansson gauges, but for large production work a complete set of master check gauges are made. These check gauges have "go" and "not go" limits to check each dimension of the working gauge, and it is evident that they must be made to an extremely high order of accuracy.

As a practical example, take the case of the manufacture of a shaft 1 inch in diameter to fit into a bearing. The tolerance would be say 0·005 inches. The snap gauges will therefore have the dimensions 0·995 inches for the "low" and 1·000 inches for the "high," and these sizes must be correct within one-tenth of this amount. The master check will

FIG. 17.

therefore have pairs of limits, one pair (0·9949 inch and 0·9950 inch), and the other (1·0000 inch and 1·0001 inch). The necessity for accurate measurement in making the master check is therefore evident: starting with a moderate tolerance of one two-hundredth of an inch for the work has culminated in requiring a master check gauge accurate to one ten-thousandth of an inch.

*Simple types of gauges.*—The most extensive use for gauges is, of course, for the production of cylindrical work. Gauges for holes are of the form

shown in Fig. 16, and consist of two hardened and ground steel cylinders: the longer being the "go" size and the shorter cylinder the "not go."

An improvement on this simple type was made by Johansson, which has the advantages of lightness and economy of manufacture. The construction will be evident on examination of Fig. 17.

FIG. 18.

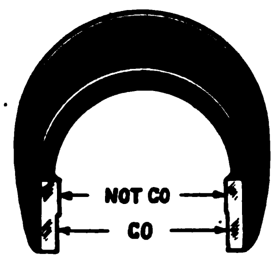



FIG. 19.

For gauging shafts, etc., external snap gauges are made of the form shown in Fig. 18. Sometimes both "go" and "not go" limits are combined as a step in a single horse-shoe for the smaller sizes (Fig. 19). Fixed gauges of the above forms when slightly worn are practically

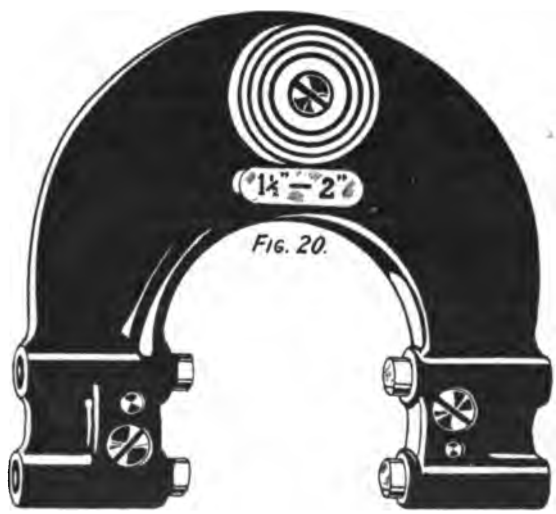



FIG. 20.

worthless, and some manufacturers have in consequence developed "adjustable" gauges, a typical example of which is shown in Fig. 20. The anvils or jaws in this case can be accurately set by screw adjustment. Adjustable gauges, however, have not come into extensive use owing to the liability of the adjustments being tampered with.

*Johansson Gauges.*—The Swedish firm of Johansson has developed a most ingenious system of end measures by means of which any desired length between 0·2 and 10 inches can be obtained in steps of one ten-thousandth of an inch. This result is achieved by the aid of a set of 81 rectangular blocks of steel of varying thickness. These can be used separately or combined together. The measuring faces of each block are approximately 0·35 inch by 1·3 inches, and the whole face is almost perfectly flat within a hundred-thousandth of an inch, and in addition the opposite faces are parallel to about the same degree of accuracy.

A standard set consists of 81 pieces made up as follows: The set is divided into four series of which the first series goes from 0·1001 to 0·1009 by increments of 0·0001 inch; the second series from 0·101 to

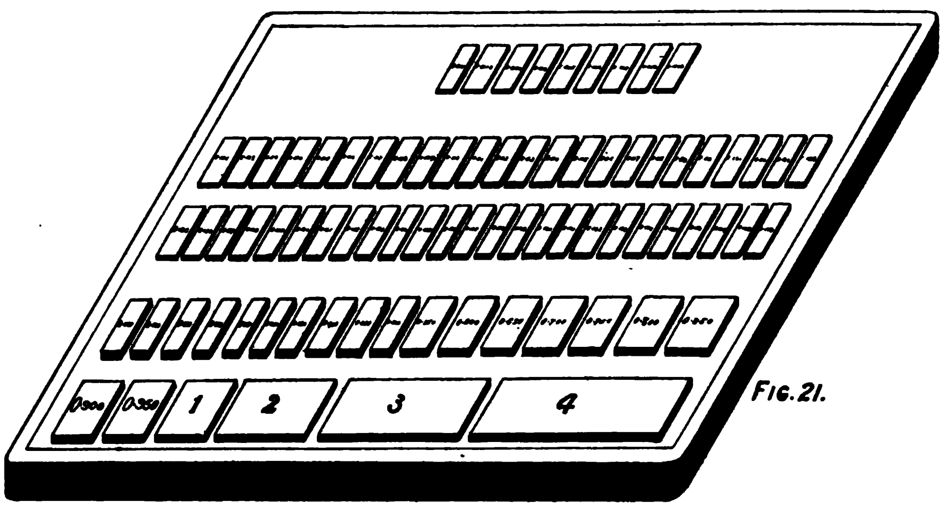



FIG. 21.

0·149 by increments of 0·001; the third series from 0·050 to 0·950 by increments of 0·05; and the fourth series consists of blocks 1, 2, 3 and 4 inches in length respectively.

A general view of a box of gauges is shown in Fig. 21. The surfaces of the gauges are such perfect planes that when assembling two gauges they adhere to each other. This adherence is the fundamental basis of the method, and only comes into action when the surfaces are perfectly clean, i.e. that there is nothing between the two gauges when wrung together that could influence the size of the combined gauge, such as grease, dust, scratches, etc., and, further, the adherence makes the manipulation of an assembled series as easy as a single rod. From a consideration of the units composing the above series it will be seen that the blocks in the first series will divide up the spaces between those of the

second series, while the third and fourth series can be divided up by the first and second series; or, in other words, any size can be obtained between 0·2 and 10 inches, rising by 0·0001 inch. By various combinations 80,000 different sizes are possible, all of which are accurate within $\pm 0{\cdot}00004$ inch, whether the size is made up of one or six blocks. A typical assembly is shown in Fig. 22. The application of these gauges to the verification of working gauges such as external limit callipers and similar parallel fixed gauges is obvious. Their use in a more complex case is illustrated by Fig. 23.

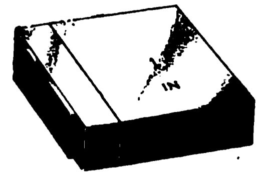



FIG. 22.


FIG. 23.

To extend the use to external measurements "points" are supplied. These "points" are double the length of the gauges and have one surface lapped to the same degree of accuracy and flatness as the gauges. By

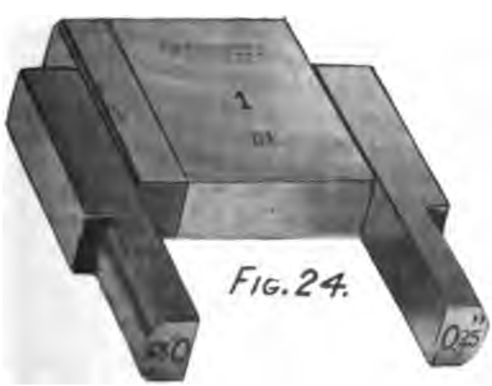



FIG. 24.

FIG. 25.

wringing them over the end surfaces of a combination or a single gauge they adhere and form an exact " snap " gauge. For half the length of the opposite sides they are rounded to a certain radius, and by adding the thickness of these points where rounded to the size of the gauge between the points an accurate " plug " gauge is made up of any desired size. A typical gauge is illustrated in Fig. 24, and an application to the verification of a plug gauge in Fig. 25.

## REFERENCES

*British Standards*

" Early Standard Yards." *Phil. Trans.*, p. 661. 1857.

" Supports of Standard Yard." Airy, *Phil. Trans.*, p. 17. 1857.

*Memorandum on a New Copy of the Imperial Standard Yard.* H. J. Chaney. Part 1, p. 30. 1905.

" A Wave-length Comparator for Standards of Length : An Instrument for fine Measurement in wave-lengths of Light." Tutton, *Phil. Trans.*, p. 1. 1909.

*Outlines of the Evolution of Weights and Measures and the Metric System.* Hallock and Wade. 1906.

*Standards of Length and their Practical Application.* Published by the Pratt and Whitney Co. 1887

*French Standards*

*Report on Standards of Length to the International Physical Congress of* 1903. Benoit.

Broch, *Trav. et Mém du Bur. Int.*, Vol. 7, p. 362. 1890.

*La Convention du Mètre, Unités et Etalons.* Guillaume.

*La Système Métrique.* Bigourdan

*Base du Système Métrique.* Mechain and Delambre.

*Notice historique sur le système Métrique.* General Morin.

*Miscellaneous*

*Invar and Related Steels.* Circular of the Bureau of Standards, No. 58. 1916.

*Light Waves and their Uses.* A. A. Michelson. The Decennial Publications, Second Series, Vol. III. University of Chicago Press. 1907.

" Comparators for the Indian Government," *Engineering*, Aug. 20th, 1915.

" An Account of the Measurement of a Geodetic Base Line at Lossiemouth in 1909, together with a Discussion of the Theory of Measurement by Metal Tapes and Wires in Catenary, Ordnance Survey," *Professional Papers*, New Series, No. 1.

*La Mesure Rapide des Bases Géodésiques*, Guillaume.

*Report on the Survey Operations*, 1912–13, *Dept. of Lands and Survey, New Zealand.* Mackenzie.

" A Silica Standard of Length." Kaye, *Proc. Roy. Soc. A.*, Vol. LXXXV. 1911.

# CHAPTER II

## THE MEASUREMENT OF SCREW THREADS

Although the screw thread is one of the simplest and most widely used of mechanical contrivances, geometrically it is an elaborate skew surface which presents unique difficulties in the way of rapid and precise measurement of its elements. Consequently the accurate gauging of screw threads has been one of the biggest problems of modern metrology. The war gave a great impulse to the precision measurement of screws in connection with screw gauges, and the advance made in methods of measurement is largely due to the work of the National Physical Laboratory, whose methods and appliances are now being adopted in works manufacturing the highest class of interchangeable parts. The limits permissible to a screw gauge are, of course, very much smaller than that allowed for the work it is to check, so that it becomes necessary to measure the various elements of a screw gauge to better than three ten-thousandth of an inch for work of precision.

### Underlying Principles of the Methods

From experience with plain ring and plug gauges it was at first thought that the simplest method of testing screw gauges would be by an adaptation of " go " and " not go " gauges of screw thread form, but experience demonstrated that such a procedure had serious inherent defects. The conclusion which has been arrived at is that the best method of making measurements on a complex surface, such as a screw thread, is not by attempting to fit another complicated surface on it, but by obtaining a magnified image of the cross-section, free from distortion, and then making the measurements on this shadowgraph. The method is identical in principle with that of the ordinary lantern-slide projector and has been highly developed.

As will be seen later, it is now possible to measure all the elements of a screw with facility, and the method has the additional advantage

over that of mechanical measurements in so much that it is possible to examine the whole of the screw surface in detail by simple inspection.

The projection method, if employed with due precaution, has great possibilities in connexion with workshop measurements, and conceivably it might be developed into a form which could be applied to the job whilst in the lathe so as to afford guidance during the actual machining. On the other hand, the method of mechanical measurement surpasses the projection method in absolute accuracy and is the ultimate standard of reference in case of doubt.

## Mechanical Measurement of Screws

The appliances described below are those in use at the N.P.L. for the measurement of screw gauges. It might be remarked that they are primarily adapted for "plug" screws. The internal threads on ring gauges cannot be completely measured by mechanical methods; it is therefore customary to supplement measurements of core and full diameters by making a Plaster of Paris cast of a portion of the thread and examining, by means of the projection method, the thread form.

In a Whitworth thread seven separate elements have to be measured:

(1) Full (or major) diameter.
(2) Core (or minor) diameter.
(3) Effective (or pitch) diameter.
(4) Pitch.
(5) Angle.
(6) Radius at crest.
(7) Radius at root.

*Full diameter.*—The measurement of this quantity is effected by means of a micrometer in a similar manner to that adopted for a plain cylinder. It is advisable to check the accuracy of the micrometer by measuring a cylindrical plug[1] of known diameter nearly equal to that of the screw. For this purpose a set of Hoffman rollers, illustrated in Fig. 26, are very useful. They are made up in sets of fifteen, varying in size from ¼ inch to 1¼ inch for this purpose at the suggestion of the N.P.L.

*Core and Effective Diameter.*—The principle involved in the measurement of core and effective diameters is shown in Figs. 27 and 28. For the core diameter two bars of triangular section, the angle at the apex being considerably less than that of the screw, are inserted as shown in the thread, and a micrometer reading is taken over these, and secondly, a reading is taken with the bars against a cylinder of known diameter.

[1] See N.P.L. Report, p. 89, 1919, for circularity tests on cylinders.

For the effective diameter, two small circular cylinders—two selected needles of known diameter—are inserted in the thread, and a micrometer reading is taken over these ; the mean diameter of the needles is determined by measuring them when suspended against a cylinder of known dimensions, and from these two readings the effective diameter can be calculated. Instead of a plain cylinder, one having a circular V groove, with an angle of 55 degrees cut in it to a suitable depth, may be employed. This is tested by means of two accurate cylinders, and its effective diameter

FIG. 26.

is found as though it were part of a screw thread. It can then be used as a reference bar.

In choosing cylinders for the measurement of effective diameter it is advisable to obtain a size which touches the flanks of the thread about half-way down, as then errors in angle have least effect on the result. Somewhat smaller cylinders may be used, but the margin is not great, as the cylinders will disappear in the thread if too small. Considerably larger ones may also be used, and will give accurate results *provided the thread form is correct.* Varying values obtained for the effective diameter by using cylinders of different sizes at once indicate incorrectness of

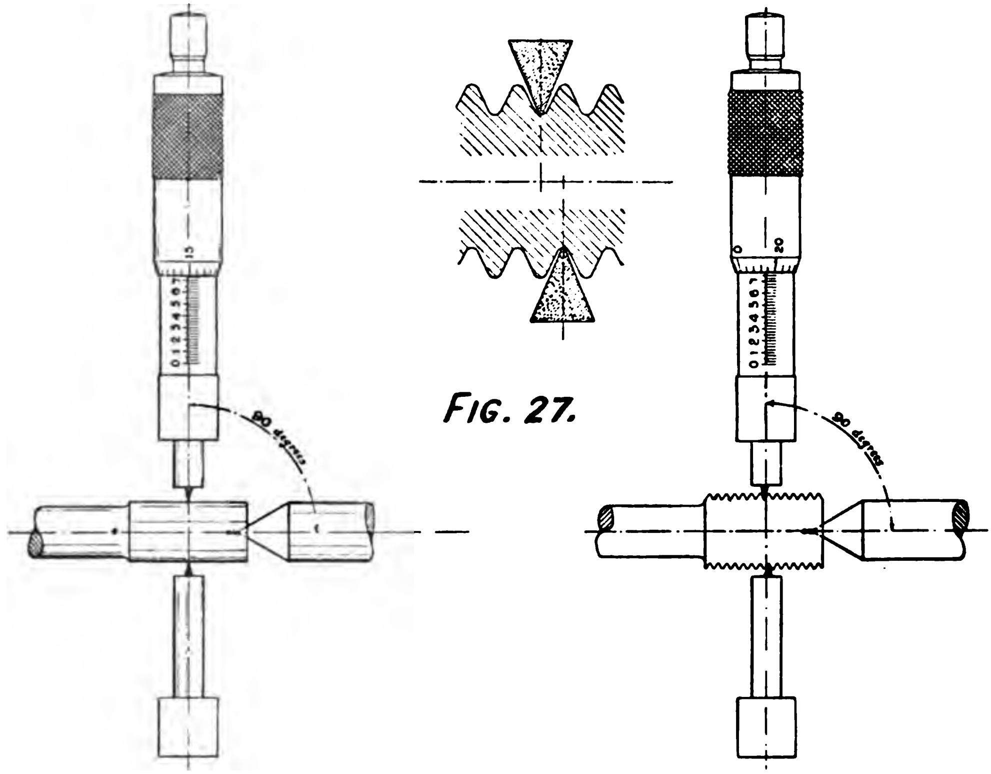



*FIG. 27.*

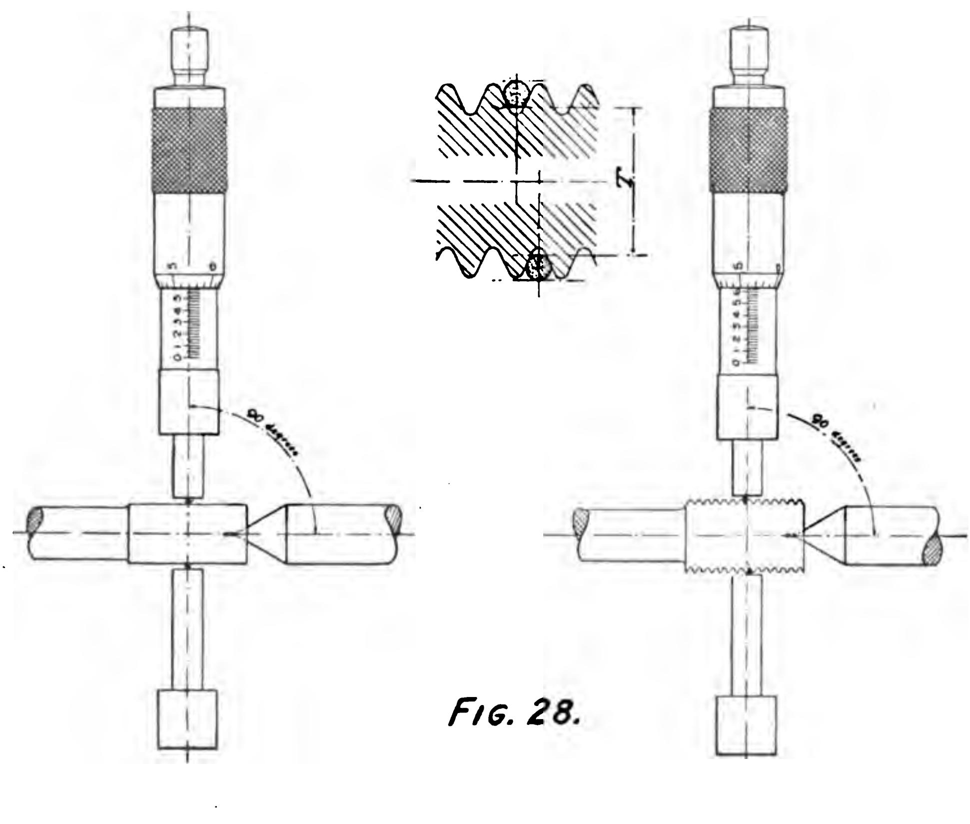



*FIG. 28.*

thread form. The diameter of the cylinder which touches the flanks of the threads of a screw of Whitworth form at points half-way between their theoretical sharp intersections is equal to 0·5637 times the pitch.

*Formula for calculation of effective diameter.*

Let $E$ be the effective diameter.

$T$ the dimension under the small cylinders, i.e. micrometer reading less diameters of needles (see Fig. 28).

$p$ the pitch of the thread.

$c$ the mean diameter of the needles.

$2a$ the angle of the Vee thread.

Then $E=T+$coefficient $P$

Where

$$P=\tfrac{1}{2}\cot a\, p-(\operatorname{cosec} a-1)c-\left(\frac{\cos a \cot a}{2\pi^2}\right)\frac{p^2}{E^2}\times C$$

to a high degree of approximation.

For a Whitworth thread form

$$2a=55^\circ$$

Thus the above formula reduces to

$$P=0{\cdot}96049\times p-1{\cdot}16568\times c-\frac{0{\cdot}086p^2}{E^2}\times C$$

The last term in this formula is usually less than 0·0001 inches. For screws of moderate rake and pitch this term may be neglected, in which case the formula is

$$P=0{\cdot}9605\times p-1{\cdot}1657\times C$$

The " Best " cylinder diameter, which in the case of a perfect Whitworth thread is the diameter of a cylinder which touches exactly half-way down the flank of the thread, is $B=0{\cdot}5637\times p$.

The values of $B$ are given in the following table :—

| Threads per inch | 40 | 36 | 32 | 28 | 26 | 24 | 22 | 20 | 19 |
|---|---|---|---|---|---|---|---|---|---|
| B inches | 0·0141 | 0·0157 | 0·0176 | 0·0201 | 0·0217 | 0·0235 | 0·0256 | 0·0282 | 0·0297 |

| Threads per inch | 18 | 16 | 14 | 12 | 11 | 10 | 9 | 8 | 7 |
|---|---|---|---|---|---|---|---|---|---|
| B inches | 0·0313 | 0·0352 | 0·0403 | 0·0470 | 0·0512 | 0·0564 | 0·0626 | 0·0705 | 0·0805 |

### Commercial Sizes and Approximate Diameters of Sewing Needles

| Size . . | 3/0 | 2/0 | 1/0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nominal Diameter in inches | 0·072 | 0·055 | 0·049 | 0·047 | 0·042 | 0·038 | 0·036 | 0·033 | 0·029 | 0·026 | 0·023 | 0·020 | 0·017 | 0.015 |

Fig. 29 shows the method of constraining a micrometer so that it can only measure at right angles to the axis of the plug screw gauge. Unless such a mounting is adopted it is necessary to use three needles—two on one side and one on the other—to ensure that the anvils of the micrometer are at right angles to the axis of the screw.

The screw gauge $S$ shown dotted is held between adjustable centres which are clamped in V grooves machined in the frame casting $C$. In the base of the frame two other V grooves are machined parallel to the line of centres. A saddle $B$, on which is machined a V groove and a flat, slides on the frame, being guided by short cylinders sliding in the grooves.

On the top of the saddle $B$ are machined two V grooves in which run steel balls. These grooves should be straight and approximately at right angles to the line of centres. The micrometer $M$ is mounted on a carriage $A$ provided with a V groove and flat which permit it to run freely on the balls. The long screw $T$ to one end of which the micrometer is bolted provide a means of adjusting the micrometer square to the screw gauge. This adjustment is essential.

In this type of machine it is convenient to suspend the vees and cylinders by cotton threads as indicated in the figure.

The type of machine illustrated in Fig. 29 can be readily modified to measure plug screws of larger diameter. The 2-inch micrometer is replaced by a micrometer head and an adjustable anvil, suitably mounted on a carriage running on balls.

### Measurement of Pitch

Attention might be drawn to the fact that pitch error may be of two kinds: ($a$) A progressive error, increasing regularly as we go along the screw; and ($b$) superposed in many cases on this a periodic error, depending frequently on some want of adjustment in the leading screw of the lathe on which the thread was cut. Examples of these errors will

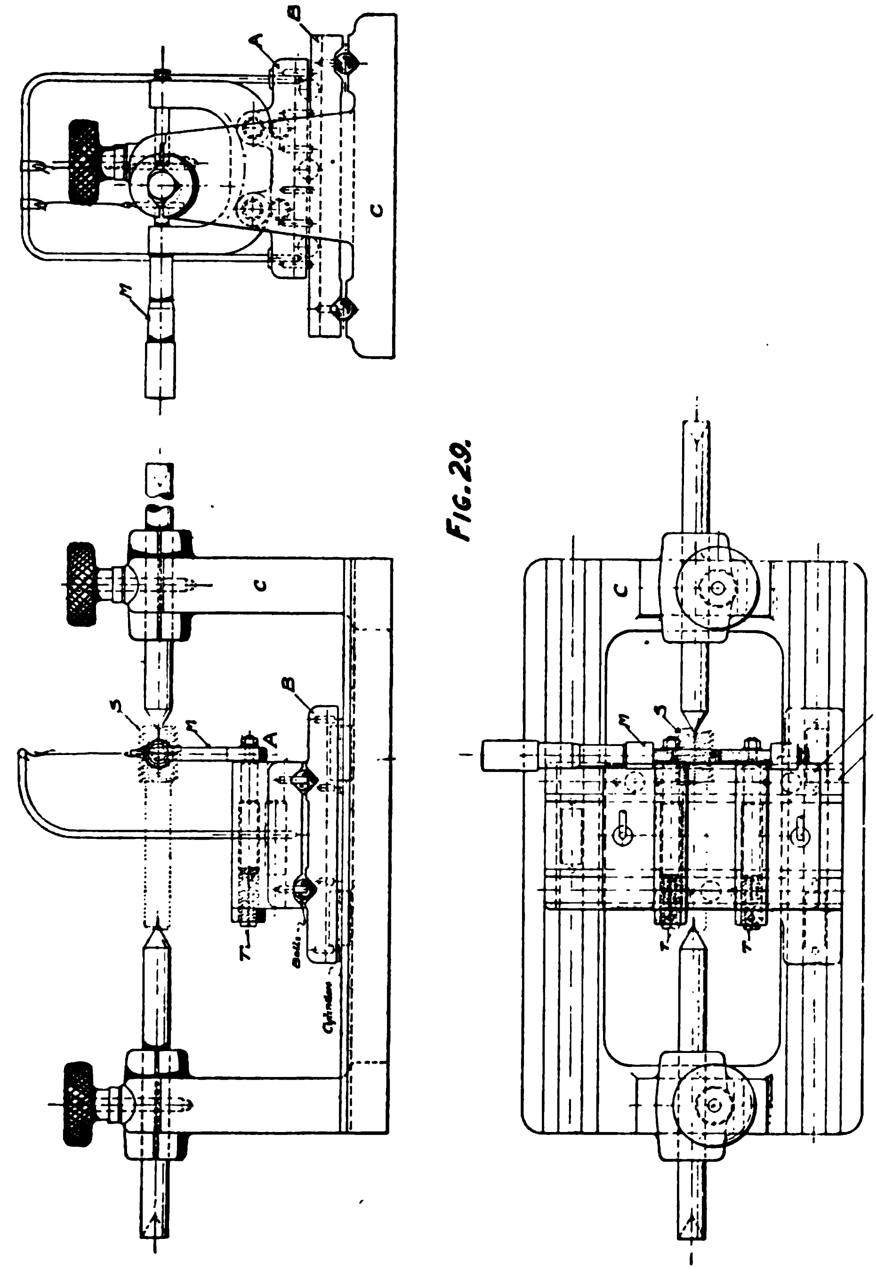



FIG. 29.

APPARATUS FOR MEASUREMENT OF FULL, EFFECTIVE, AND CORE DIAMETERS

be given later. In measuring the pitch of a screw, it is mounted on centres on a stiff bed which carries a saddle sliding parallel to the line of centres. This saddle is moved by a screw which has been carefully calibrated, and the motion is read on a large micrometer head. In its simplest form the saddle carries a pointer accurately ground to an angle of 55 degrees, with its axis at right angles to that of the screw. The pointer can slide in the direction of its own length on the saddle. The pointer is set by the micrometer with its two edges in contact with the sides of a thread and a reading taken. It is then withdrawn, the micrometer is turned until the pointer is opposite the next thread, when it is again adjusted, and so on. A series of readings taken thus gives the distances between the consecutive roots of the thread, i.e. the pitch, and from these the pitch error is calculated. The method is slow and not very accurate, and it is difficult to set the pointer.

An improved form of this apparatus is shown in Fig. 30, and this works as follows :

The screw is mounted as before, but the feeler carried by the saddle takes the form of a small spherical ball at the end of a bent lever. The ball is held pressed into the threads of the screw by a light spring, and as the saddle is traversed along the ball moves to and fro, always remaining in contact with the screw. The ball is too large in diameter to reach the bottom of the thread. In its motion it slides down one flank of the thread until it is arrested by contact with the opposite flank, when it immediately begins to move up this flank ; this change of motion is very sharply defined. By noting on the micrometer screw the positions of the slider at which these changes of motion take place, we have a means of measuring the pitch of the screw. To effect this a mirror is attached to the arm carrying the small sphere and rotates backwards and forwards as the arm moves. A spot of light reflected from the mirror on to a scale moves in one direction, then stops and moves back ; after a time its motion is again reversed, and so on. The sharp reversals caused by the point of contact of the sphere passing from one flank of the screw to the opposite flank are clearly defined, and by their means an accurate measure of the pitch is obtained. Fig. 31 gives one of the curves actually obtained at the N.P.L. in this way. This particular screw gauge had 18 threads to the inch.

It will be observed that the curve shows periodic variations of 6 to the inch, and the lathe on which the thread was cut had a leading screw of 6 threads to the inch. It is generally found that the most pronounced periodic error—an alternate lengthening and shortening of the pitch of

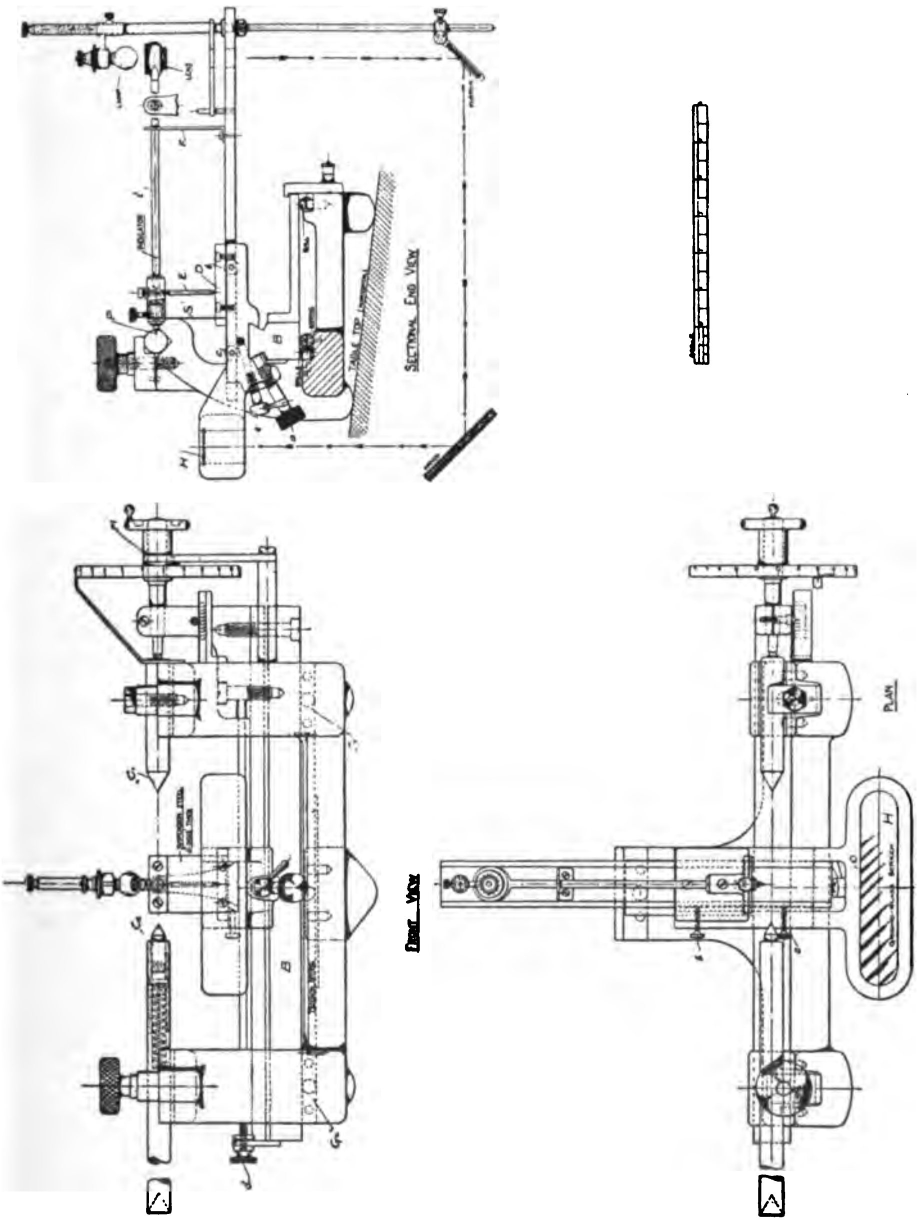
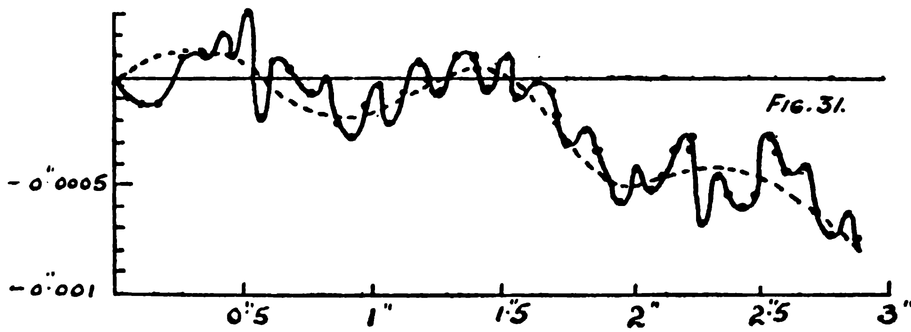



Fig. 30.—APPARATUS FOR THE MEASUREMENT OF PITCH

a screw—repeats itself every revolution of the leading screw of the lathe. This may be due to one or any combination of the following :—

(1) Intrinsic error of the leading screw ; being cut incorrectly.
(2) Incorrect centring of the gear wheel on the lead screw.
(3) Lead screw not revolving truly about its axis.
(4) Imperfect adjustment of the bearing which takes the end thrust.

The last mentioned is the most common source of the error. In the case of the screw gauge whose errors are depicted in Fig. 31, the periodic errors are not serious but somewhat variable. Another interesting feature




to be noted about this curve is the existence of a distinct underlying period of one per inch which is shown dotted. Such error may be caused by rotating parts being out of balance or mounted eccentrically.

### Measurement of Angle

The apparatus illustrated in Fig. 32 is used for measurement of thread angles and for general observation of the form of the thread. The screw gauge *S* is held between centres which slide in holes or vees in two blocks $B_1$ and $B_2$. The two blocks are clamped on to a length of screwed rod *R*, so that they move solidly together. The screwed rod also acts as a rack and is moved longitudinally by means of a pinion *P*. This pinion is inclined and acts as one support of the moving screw holder. The other supports $L_1$, $L_2$ are L-shaped grooves which carry the two rods $C_1$ $C_2$ holding the screw. Five degrees of freedom are constrained by these five point contacts, leaving only one linear motion possible. The transverse motion is provided by mounting the microscope on a base plate *K*, sliding between bevelled guides. The third motion, that of rotation, is obtained by turning the eyepiece of the microscope which carries the cross wire *W*. This rotation is measured on the graduated scale. The axis of the microscope is set at right angles to that of the screw, and care

must be taken that the light which enters the microscope comes along the rake of the thread.

To make a measurement of the angle, the microscope is first focussed

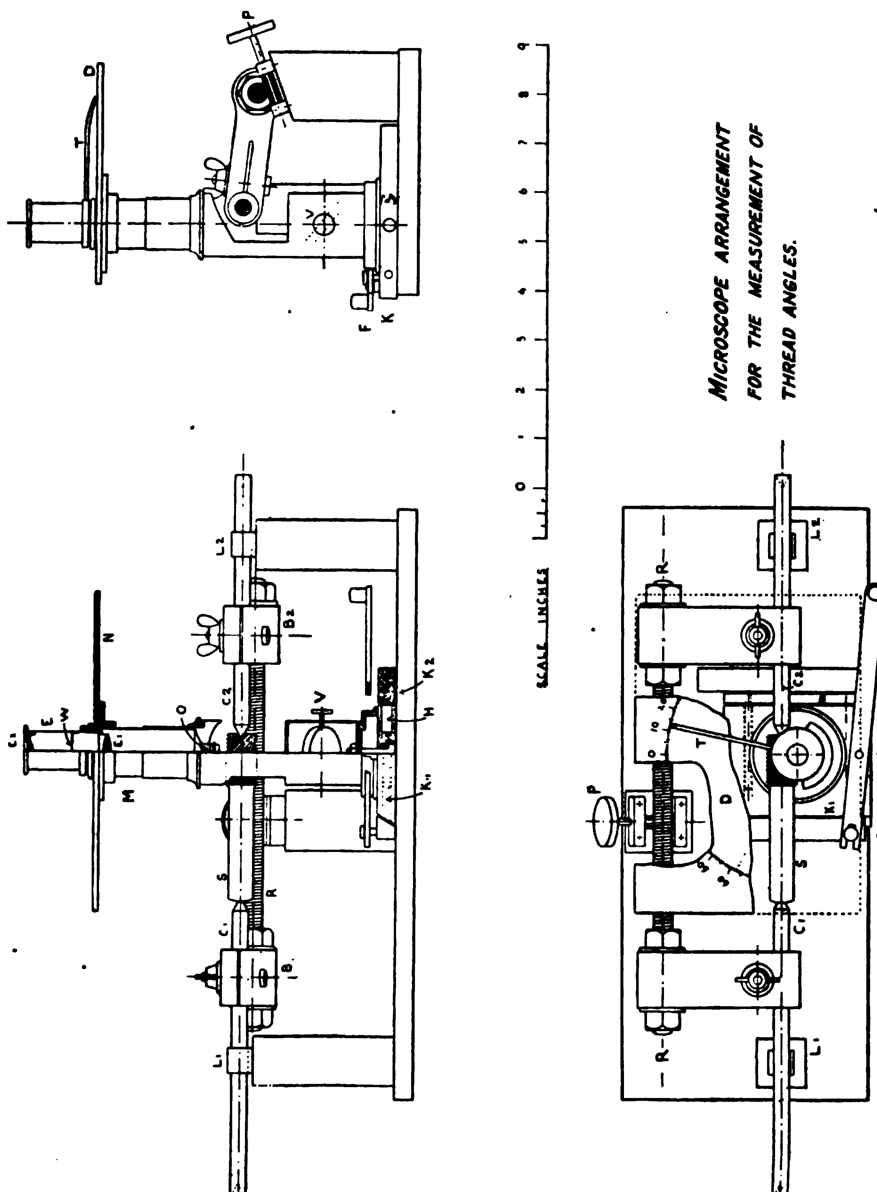



Fig. 32.

on one of the centres which carry the screw; it is then moved aside, and the screw is put in position and traversed by means of the adjustments until in the field of view. This method of focussing ensures that

an axial section of the screw is under examination. The microscope is then rotated about its axis until the cross wire is along the flank of one of the threads and a reading is taken; the tube is turned and the screw traversed until the cross wire lies along the opposite flank, and a reading is again taken; the difference between these gives the angle of the screw. By setting the cross wire to run along the crest of the thread and taking a reading, the squareness of the threads to the axis can be verified, while the general shape of the thread is obvious to the eye.

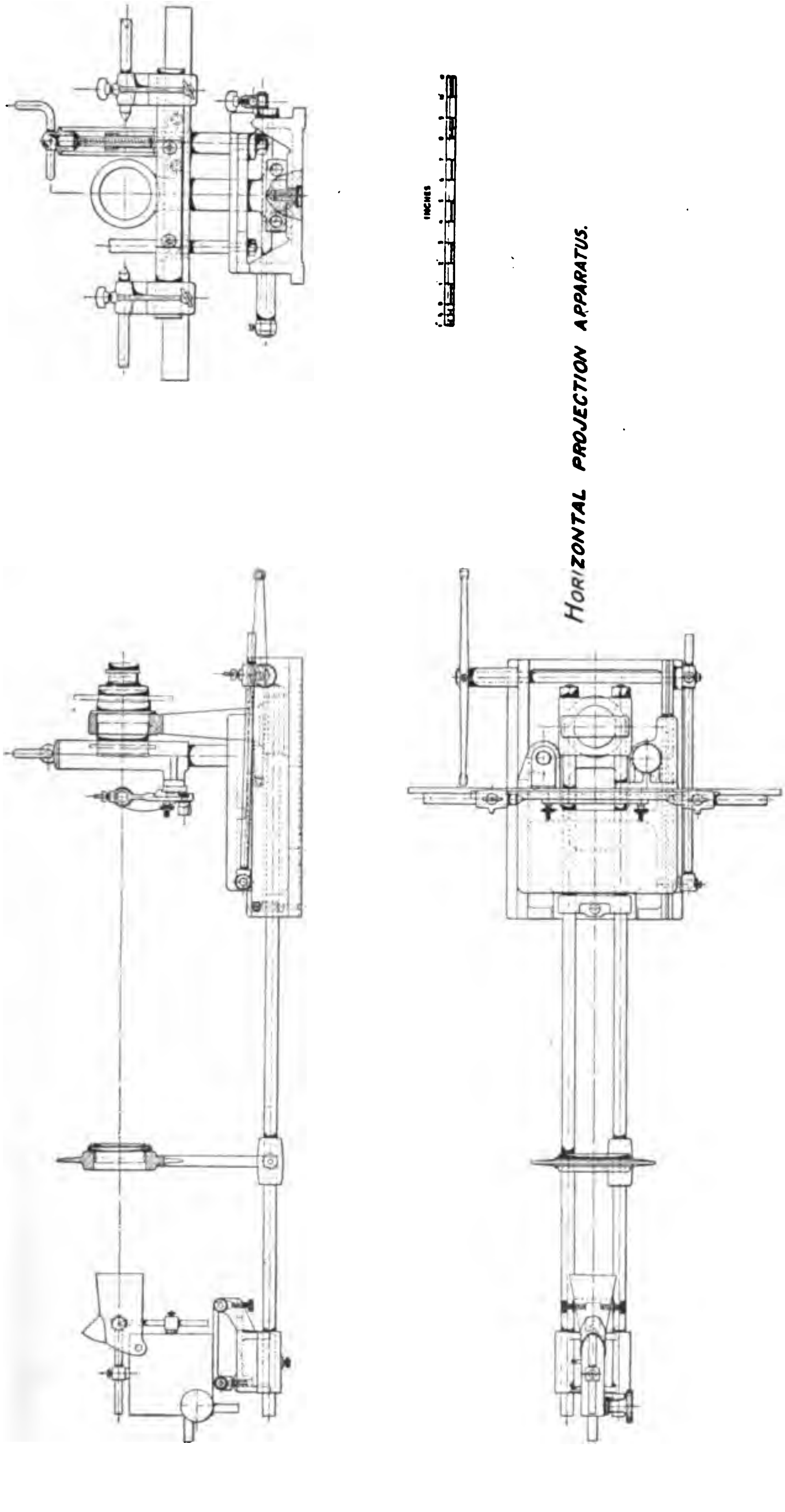
By attaching the part carrying the screw to two slides at right angles, one parallel to and the other at right angles to the axis of the screws, fitted with accurate micrometers, measurements of the diameters and pitch of a small screw may be made.

### Optical Projection Methods

The optical method of measuring screw threads has the merit of simplicity and sufficient accuracy for most purposes. The horizontal type of apparatus is a development of the familiar optical lantern, adapted for the projection of the outline of a solid object instead of a transparency. A magnification of about 50 is generally aimed at, as this has been found to be the most convenient value for ordinary screw gauges. The actual magnification is determined by the quality of the projection lens and the diameter of the screw to be projected. For any lens the definition of the image falls off to a marked extent as the diameter of the gauge is increased. The lens should have a focal length of between 2 and 4 inches, and those of large aperture which have exceptionally good central definition have proved most satisfactory.

The apparatus for horizontal projection (without the screen) is shown in Fig. 33. The gauge under test is mounted on centres, so that the axis is exactly at right angles to the axis of the lens.

By means of suitable slides the gauge can be moved in a plane parallel to the screen either in the direction of its axis or at right angles to its axis. The beam of light has to be "raked" so as to graze either the upper or the lower side of the screw, and this can be done by swivelling the arm, which carries the arc lamp and condenser, about a vertical axis through the lens. The magnification is adjusted by the use of a parallel cylinder of known diameter instead of the gauge. Distortion is indicated by the width of the image of the cylinder being larger or smaller at the centre of the field than at the edges. The whole field may be considered free from distortion if the width of the images of a cylinder whose diameter covers about two-thirds of the field, and also of a much smaller




HORIZONTAL PROJECTION APPARATUS.

Fig. 33

cylinder, are both free from measurable variations across the whole width of the field. The accuracy of the adjustment of the beam along the rake of the screw is shown when both flanks of the screw thread at the centre of the field are equally well defined and both in focus.

The angle and squareness of the thread may be measured by a protractor such as is shown in Fig. 34. The white disc $A$, about 8-inch diameter, bears a thread-form diagram, and is arranged to pivot centrally on a board $B$. The disc is recessed into the board so that their upper surfaces are flush. The board runs on a ledge as shown so that the diagram can be adjusted to the shadow in a horizontal direction. The disc has a line $aa$ drawn on it which answers the same purpose as the cross wire of the microscope (see p. 34) when measuring angles.

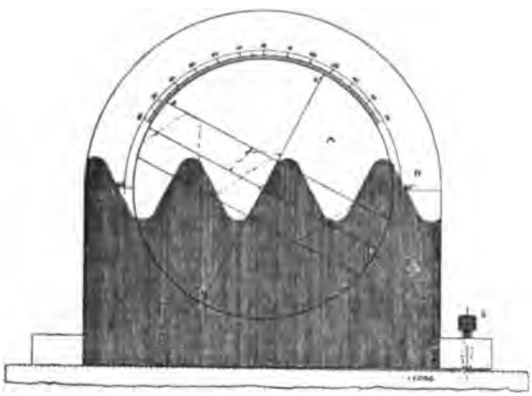


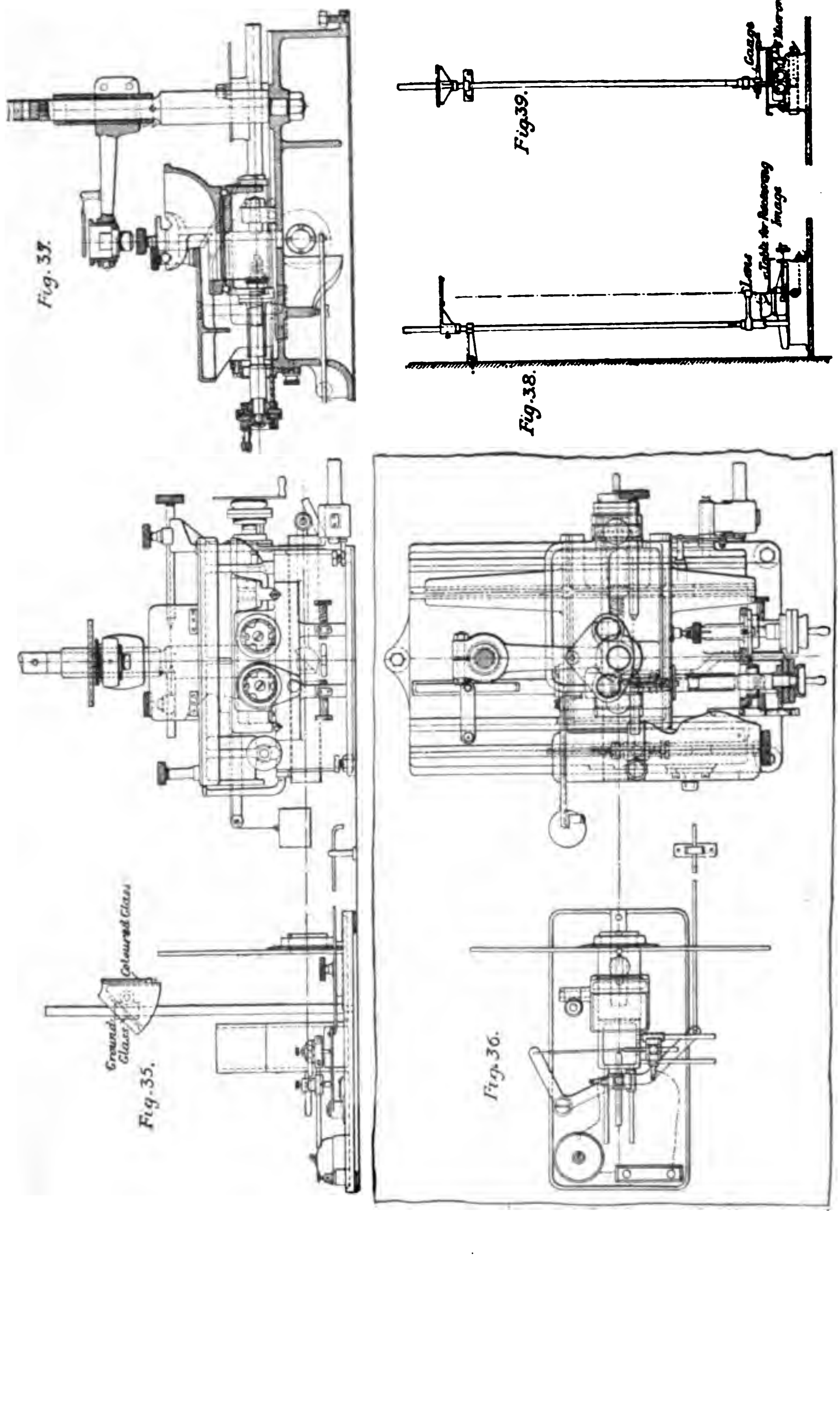
FIG. 34.
PROTRACTOR FOR THE MEASUREMENT OF ANGLE AND SQUARENESS OF THREAD.

To measure the angle and its squareness the line $aa$ is first set to read 0° on the scale marked on the board $B$. The screw $S$ (or some equivalent means), shows diagrammatically a means of adjusting the board until the line $bb$ becomes parallel with the crests of the shadow. The shadow has to be moved up or down to bring the crests of the threads into coincidence with this line. The disc is then rotated until the line $aa$ coincides with the two flanks of the threads in turn, readings being made on the angle scale at each setting. In this manner the angle which each flank makes with the axis is measured directly. The sum of the two angles gives the angle of the thread.

The machine serves also for testing plate or profile gauges.

## VERTICAL PROJECTION APPARATUS

An elaboration of the previous apparatus in which micrometer movements are applied for measuring effective diameter and pitch is shown in Figs. 35–46. In this case the gauge is mounted between centres just above a horizontal table, the illumination being (approximately) vertical. The image is reflected down on to the table from a horizontal mirror placed some distance above the gauge. Thus gauge and image are close together and both simultaneously under the control of the observer.




VERTICAL PROJECTION APPARATUS.

With this apparatus measurement of the diameter and pitch of screw gauges can be made to almost as high a degree of accuracy as can be obtained by the mechanical methods.

Figs. 35 and 36 show the apparatus in elevation and plan, Fig. 37 is a vertical section through the vertical post and the second micrometer, and Figs. 38 and 39 are explanatory diagrams of the complicated arrangement. The arc lamp, to the left of the machine, which supplies the beam of light, is of special design. The carbons are adjusted by the observer by means of the horizontal rod connected to the bell-crank lever which operates the slides carrying the carbons. The reflector above the lamp (Fig. 35) which consists of a ground glass and a coloured glass, enables the observer to watch the arc itself. The beam is rendered parallel by a condenser; the reflecting prism of 45 degrees is placed in the base of the machine, as Fig. 35 shows. If we look at Fig. 38 we see on the top the reflecting mirror; lower down the holder of the lens (a kinematograph lens) above the centre carrying the gauge under examination. To the left will be also seen another centre which is used for holding gauges of more than 2-inch diameter. Further down will be seen the table (see also Fig. 37), the movement of this table being controlled by the handle shown best in Figs. 35 and 36. To the right of Fig. 35 will be seen the incline for adjusting the beam of light reflected from the prism to the rake of the threads of the gauge under examination, a roller bearing on the inclined plane being connected to the prism by the lever shown in dotted lines. The two micrometers, to which reference will be made later on, are shown clearly in Figs. 35, 36 and 37.

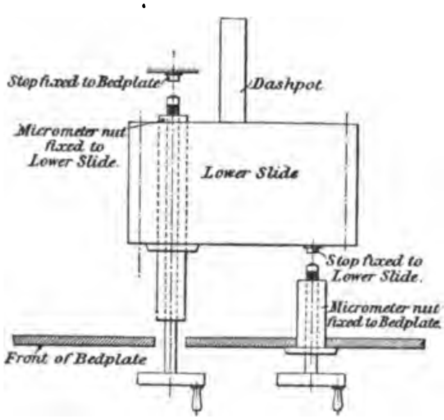
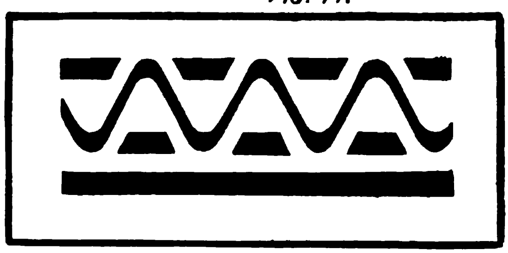



FIG. 40.

The body of the machine consists of a bedplate carrying two slides. The lower slide (Fig. 40) moves horizontally in a direction at right angles to the axis of the screw gauge; this motion is controlled by the pair of micrometer screws whose handles project in front. With the help of these screws rapid measurements can be made on the diameters of the screw gauges up to 2 inches in size. In measuring screw diameters the lower slide need not be fed right across by rotating the micrometer screws. The slide is simply moved across, first to one side, and then to the other,

and the sum of the micrometer readings gives a measurement of the motion of the slide from one side to the other. The actual movement of the slide is accomplished by a "throw-over" gear, consisting of a weight and a set of levers shown to the right of the machine (Figs. 35 and 36); this motion is steadied by an adjustable oil dash-pot at the rear of the machine, to prevent any jar on the micrometer spindles when they come in contact with the stops. The second upper slide rests on the lower slide and can move along it in a direction parallel to the axis of the gauge. This movement is controlled by a third micrometer seen on the right of the machine in Figs. 35 and 36. It is by this micrometer that pitch measurements are made, and the pitch-micrometer screw has to be accurately calibrated for the purpose. Errors in the diameter-micrometer are of less importance, since the machine is set up on a plain cylindrical plug of approximately the same diameter as the gauge to be measured.

FIG. 41.



Standard thread-form diagrams, such as Fig. 41 illustrates, are used on this machine, and by their aid errors in the form of the thread, as small as 0·0001 inch, can be detected. The magnification used is 50 diameters; this can be adjusted by varying the height of the reflecting mirror.

The thread-form diagram should be held against the screen and allowed to rest on an adjustable straight edge fastened to the latter. A screw or an eccentric adjustment is provided at $A$ (Fig. 42), and a pivot or screw at $B$. The screen itself must be adjustable vertically. The thread shadow should be made to touch the diagram on the full diameter line *aa* by the aid of the vertical adjustment and of the straight-edge adjustment $A$. A simple side shift of the diagram on the straight edge will then enable the observer to adjust the diagram as in Fig. 43; the variations from the standard form can thus be observed. The black portions *bb* indicate an excess of metal, the white *ww* portions mark where metal is missing from the thread; the overlapping at *bb* can only be seen in a suitably darkened room. As regards actual measurements, it has to be borne in mind that, when the thread-form is mounted on a thick board,

the magnification of the image of the gauge will be less on the diagram than on the screen itself. This error may be corrected by moving the mirror further from the screen, one-half the distance of the thickness of the diagram used. With 20 feet distance from lens to screen, 0·1 inch thickness of the thread-form diagram will reduce the magnification from 50 to 49·98 ; this error would amount to 0·004 inch on a 10-inch measurement on the screen, and is therefore negligible for ordinary screw-thread inspection.

The thread-form diagram enables the observer clearly to discern all the variations from the standard form, including crests and roots. When only variations in angle, squareness and straightness of flanks are to be studied, a " shadow set square " may be used instead of the thread-form

Fig. 42.

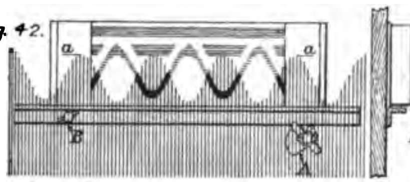



Fig. 44.

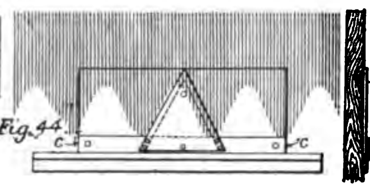



Fig. 43.

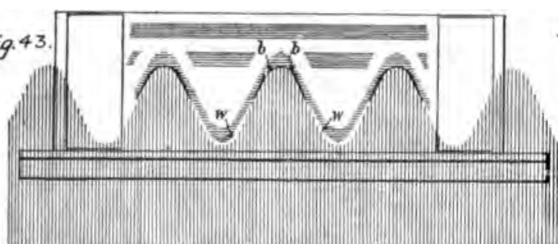



Fig. 45.

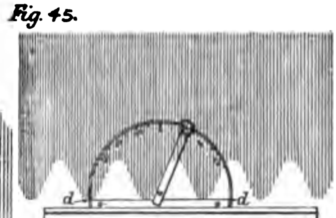



diagram. The straight edge *cc* of this set square (Fig. 44) is made to coincide with the crests of the screw shadow, and the set square is shifted along the adjustable straight edge, until there is only a narrow band of light between the shadow of the thread flanks and the shadow of the set square edge. To obtain measurements of angles in degrees a " shadow protractor " (Fig. 45) is used ; the screw-gauge shadow appears on the white opaque celluloid face of the protractor, and also the shadow of the straight edge *dd* and the edge of the protractor arm. In the thread-form diagrams usually employed the thread, the full diameter, and the core edges are duplicated, making the snake-like pattern shown in Figs. 42 and 43. The second set of edges and the plain band of the top of the diagram are used for diameter measurements on the special vertical projector for screw gauges and are not required for thread-form examination in the horizontal projector.

### PROJECTION APPARATUS FOR THE RAPID COMPARISON OF SCREWS

An ingenious method has been devised by Mr. R. P. Wilson[1] for the rapid comparison of screws ; one machine being capable of testing several thousand screws per day. The apparatus as constructed by Messrs. Adam Hilger is illustrated in Figs. 47–50.

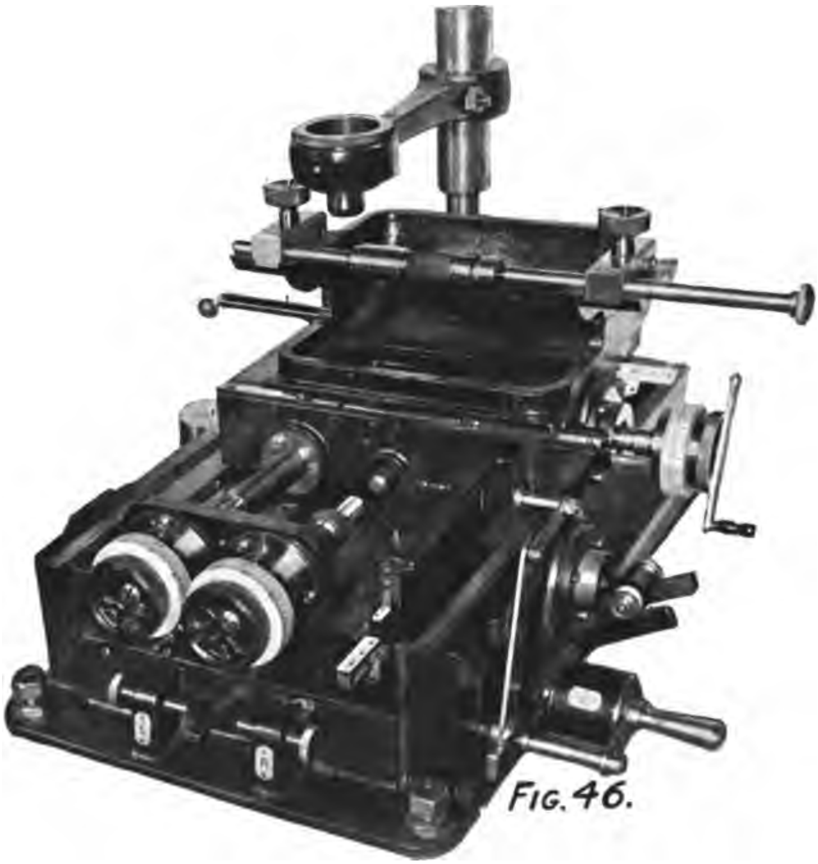


FIG. 46.

VERTICAL PROJECTION APPARATUS.

The principle of the method will be understood from Fig. 49. The apparatus essentially consists of two projection lenses which are mounted side by side, but are separable by turning a screw, and are set to approximately the distance of the mean diameter of the screw-thread under test ; images of the two opposite contours of the screw are then projected through two prisms so that the images intermesh. The apparatus is adjusted by putting the screw gauge in position and adjusting the two

[1] M. of M.

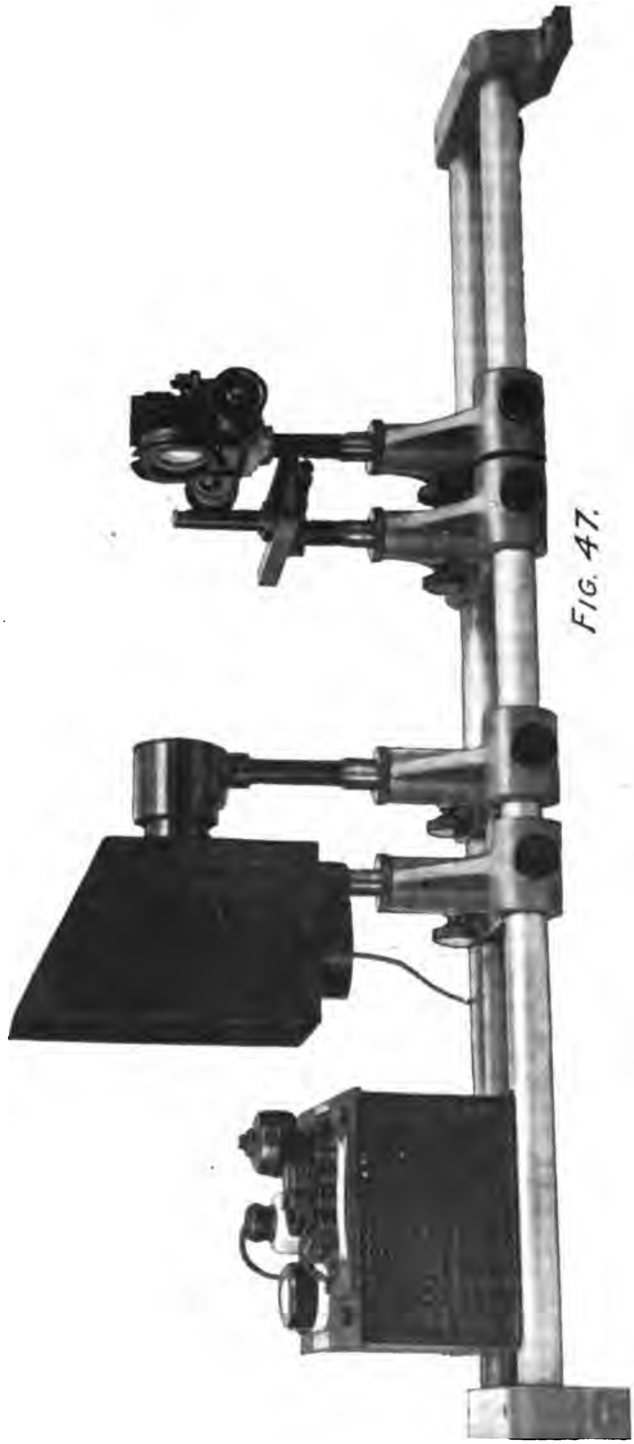


FIG. 47.

lenses and prisms until the projected images intermesh exactly, neither overlapping nor leaving free spaces in between ; an overlap of the images indicates that the diameter of the screw is too large, and a gap that the diameter is too small.[1]

FIG. 48.

The screws to be tested can be placed quickly in position, one after the other, and the tests which reveal also defects in the threads can be conducted with many times the rapidity of other methods. The two lenses mentioned are really the halves of one lens which is cut in a vertical diameter ; the two halves are elastically held together by a strip of sheet metal bent to an acute angle.

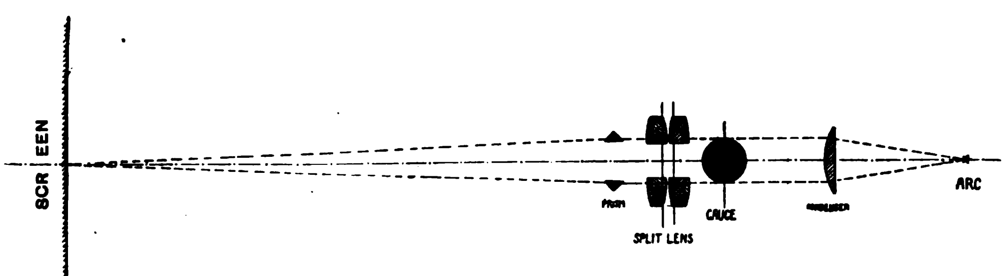



FIG. 49.

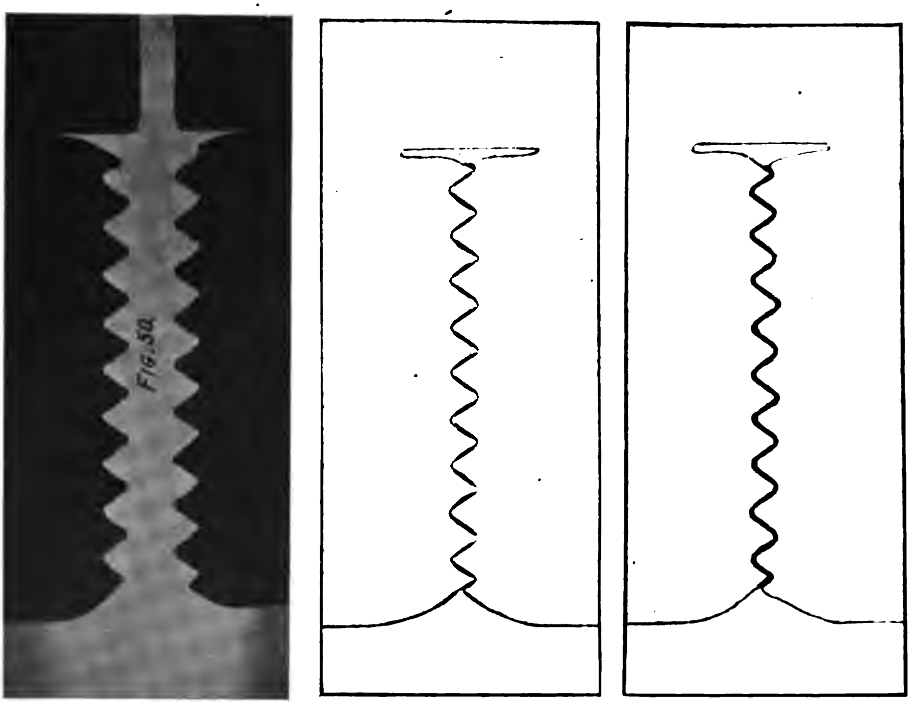
From a consideration of the diagram showing the paths of the light rays (Fig. 49) it will be seen that the two images formed by the projection lenses alone would be the right and left profiles of the screw, the images being separated by a distance equal to the pitch diameter of the screw.

The two prisms, however, receive the rays from the projection lenses

[1] It should be remarked that the light does not pass along the rake of the threads, which is a defect. But since the machine is primarily intended for checking work, not gauges, the accuracy is sufficient.

and reverse the images by fine adjustment of these prisms about a vertical axis; the two profile images can be got into "mesh" and the final adjustment during measurement made with the large micrometers shown in Fig. 48. Adjustment is first effected with a standard screw, and it can then be ascertained by inspection whether the screws under test are of the correct diameter.

Fig. 50 illustrates the images obtained when the machine has been set to compare diameter. The first screw is very much undersize; the second is correct, since the root and crest images just touch each other, the overlap on the flanks being due to interference caused by the light not being projected along the rake; while the third diagram shows a slightly oversize screw resulting in overlapped images.




Undersize Correct Oversize

## REFERENCES

Glazebrook, Sir R. T. "Limit Gauges." Address to Section G, British Association, 1916, *Engineering*, Sept. 8th and 15th, 1916. Also various summaries of N.P.L. reports published in *Engineering*.

*Notes on Screw Gauges*, National Physical Laboratory Publication, 1917.

# CHAPTER III

## MEASUREMENT OF AREA

THE engineer is concerned with the measurement of area in various ways, such as estimation of work done in steam engine cylinders from the integration of the indicator pressure diagram; quantity evaluation from the area of the charts of recording instruments; determination of the volume of material to be moved in preparing cuttings, embankments and railways; and finding the second and third moments of areas to obtain the centre of gravity and moment of inertia about a given axis for structural calculations and ballistics.

The area of an irregular figure is generally estimated by arithmetical calculation, by adding together the areas of a large number of strips into which the area has been divided. Simple rules have been devised for effecting this calculation. Of these Simpson's Rule is perhaps the best known. This rule is based upon the fact that arcs of parabolas can be drawn, to fit the curve approximately, through the tops of a number of equidistant ordinates taken three at a time. For example, let $A\ B\ D\ E$ (Fig. 51) be the figure whose area is required. Draw ordinates dividing the area into an even number of strips of equal width. Thus there will be an odd number of ordinates, including the first and last. Numbering the ordinates $y_1$, $y_2$, $y_3$ . . . Add together the first and last ordinates,

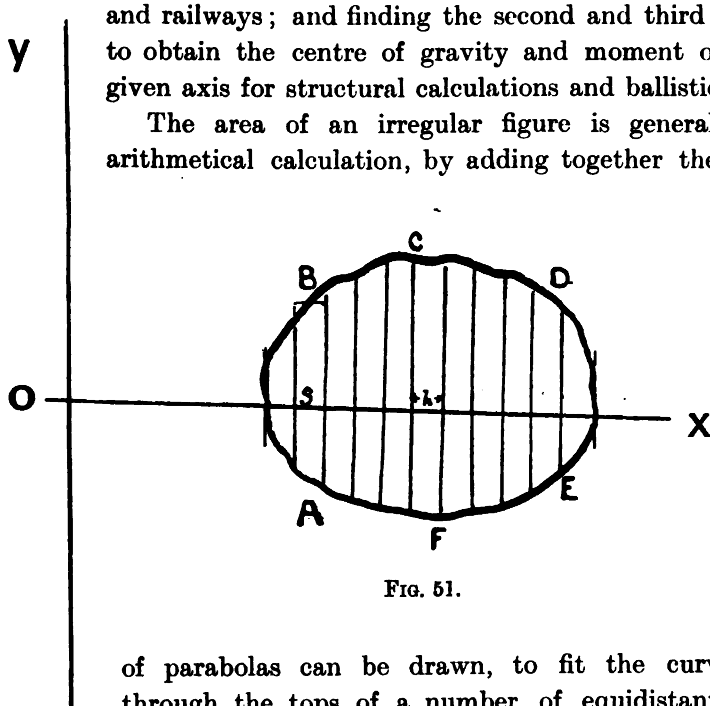



FIG. 51.

twice the sum of the other odd ordinates, and four times the sum of the even ordinates; multiply the result by one-third of the distance between two adjacent ordinates. The result gives the area of the figure thus:

$$\text{Area}=A=\frac{h}{3}\left[y_1+y_n+2(y_3+y_5+\ .\ .\ .)+4(y_2+y_4\ .\ .\ .)\right]$$

where $h$=distance between the ordinates.

The above and similar methods are cumbersome and involve a considerable amount of arithmetic and measurement; mechanical instruments are therefore almost universally employed when areas have to be

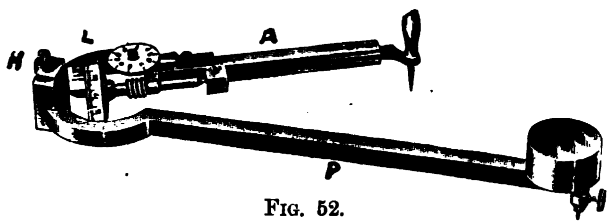



FIG. 52.

measured. The best known instrument for this purpose is the Polar Planimeter, invented by Dr. Jacob Amsler in the year 1854. This is shown in its simplest form in Fig. 52. The device consists of two arms $A$ and $P$, hinged together at $H$. The tracer arm $A$ carries a small wheel $L$ which is mounted with its axis parallel to a line through the tracing point and the hinge, and free to roll on the paper. The polar arm $P$ is provided with a needle point which is pressed into the paper and the instrument swings about this fixed point when in use.

The following is a simple theory of the action of the instrument. Let $O$ (Fig. 53) be the fixed point of the polar arm, $O\ A\ P$ the planimeter, $A$ the joint.

1. Fix the joint $A$ and move $P$ to $P_1$ on the arc of a circle, centre $O$, then if $OA$ turned through an angle $Q$ the dial at $A$ would register an angle $M\ Q \cos \phi$, if the angle between $A\ P$ and $O\ A$ produced was $\phi$, and $M$ was some constant.

2. Fix the arm at the joint $O$ and move $P_1$ to $P_2$ on the arc of a circle, centre $A$; the wheel will record a reading $C$ say.

3. Fix the joint $A_1$ and move $A_1$ back to $A$, and $P_2$ to $P_3$; the wheel at $H$ would move back an angle $M\ Q \cos \phi^1$, if $\phi^1$ was the angle between $A\ P_3$ and $O\ H$ produced.

4. Fix the joint $O$ again, and move $P_3$ to $P$ on the arc of a circle centre $A$, the dial would move back through an angle $C$ and cancel the

reading made in passing from $P_1$ to $P_2$. In completing the circuit of the finite area $P\,P_1\,P_2\,P_3$, the dial therefore has registered an angle $M\,Q$ (cos $\phi -$cos $\phi^1$)

But the area $P\,P_1\,P_2\,P_3=$area $P\,P_1\,Q_1\,Q$

$$=\tfrac{1}{2}\,Q\,(a^2+2ab\cos\phi+b^2-a^2-2ab\cos\phi^1-b^2)$$
$$=ab\,Q\,(\cos\phi-\cos\phi^1)$$

if $O\,A=a$, $A\,P=b$.

Then if $M=ab$, the dial would register the area $P\,P_1\,P_2\,P_3$.

Any irregular area must be supposed to be made up of infinitesimal elements in the form of $P\,P_1\,P_2\,P_3$. If a planimeter is made to describe

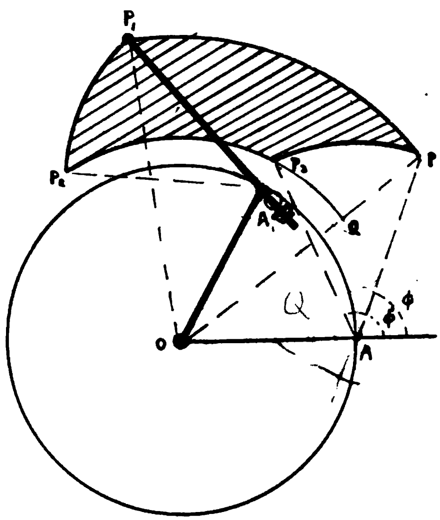



FIG 53.

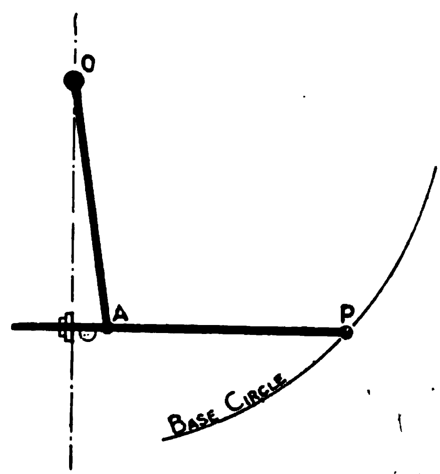



FIG. 54.

a circle about the fixed point or pole with the plane of the recording wheel along the radius, the motion of the wheel will be entirely slipping and therefore the indication will be zero. This circle (Fig. 54) is termed the zero or base circle for that particular length of arm and adjustment of the planimeter. It is obvious that if it is contained in the area to be measured the reading of the instrument will be the difference between the true area and the area of the base circle. The area of the base circle must therefore be added, with the correct algebraical sign, to the reading of the wheel.

Polar planimeters are liable to errors due, first, to the axis of the recording wheel not being parallel to the line through the tracing point and the hinge; this error can be reduced to a very small amount by taking the mean of two sets of readings with the arms reversed, as in

Fig. 55. The original form of the Amsler planimeter did not permit of this reversal, but modern instruments are designed with this object in view and this type of instrument is known as the compensated planimeter.[1] A typical example is shown in Fig. 56. *P* is the polar arm, *b* is a small weight for pressing the needle into the paper. *A* the tracer arm, *L* the

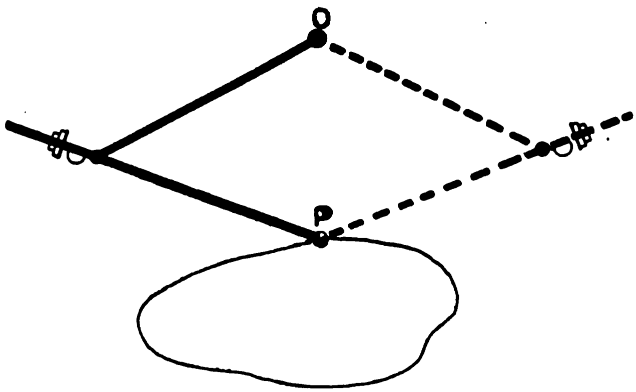



FIG. 55.

recording wheel and *D* the hole into which the ball-ended projection on the tracer arm fits. The small screw at *C* enables the parallelism of the wheel axis to be actually corrected if found necessary by reversed reading as above.

The second source of error is due to slipping of the wheel, especially on rough or crinkled paper. Special instruments are made in which the recording wheel rolls on a smooth disc, as shown in Fig. 57. This disc derives its rotation through gearing from a wheel which rolls on the dia-

FIG. 56.

gram, and the recording wheel swings around a vertical axis through the same angle as the tracer arm. The wheel therefore rolls on a circle, on the disc, whose radius varies with the angular position of the tracer arm. The use of these instruments is somewhat limited, and the simple form generally suffices for ordinary work.

[1] The modern development of the planimeter is largely due to Conradi, Switzerland.

The accuracy of the result obtained by measuring a given area depends to a large extent on the possible accuracy of reading the wheel, and although this is provided with a vernier it is desirable to make the reading of the wheel as big as possible, for small areas, by shortening the arm of the planimeter to suit the area being measured and then use a multiplying factor. This can be easily effected on the planimeter shown in Fig. 56, by sliding the tracer arm in or out, and this adjustment has the

FIG. 57.

additional advantage of allowing the arm to be set to such a length that the reading is correct in certain alternative units, such as square inches or square centimetres. The setting can be quickly verified from time to time by the use of a simple accessory provided. This consists of a small metal strip with a needle point projecting at one end and a series of small holes drilled along its length to hold the tracing point of a planimeter, as shown in Fig. 58. By pressing the needle point into the paper and inserting the tracing point into one of the holes, the tracing point can be made to circumscribe a circle of definite area and the reading on

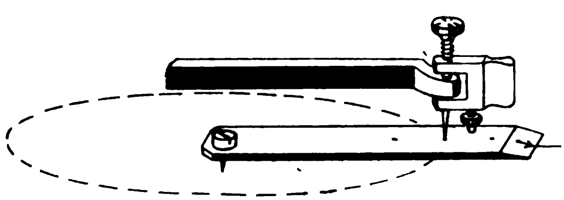


FIG. 58.

the dial of the planimeter can be compared with this known value. A series of holes are provided to correspond to different units. Several slightly modified forms of the polar planimeter are obtainable for special purposes. For instance, adjustable planimeters can be fitted with two points, one on the tracer arm and the other on the frame for setting the length of this arm to the width of indicator diagrams as in Fig. 59; in

which case the reading is so arranged as to be equal to the mean height of the diagram in fortieths of an inch when the planimeter is taken round the diagram. The mean pressure during the stroke being thus obtained immediately by multiplying by the scale of the spring used in the indicator.

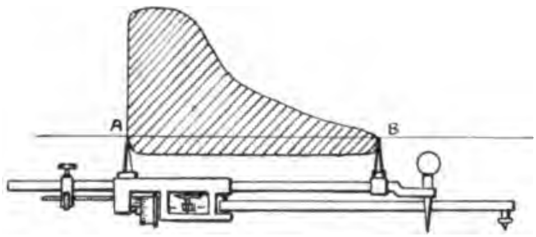



FIG. 59.

Another ingenious modification is that used for finding the mean ordinate of circular charts, and is shown in Fig. 60. The tracer arm is in this case made of inverted *U* section and slides radially on a knob *D* fixed in the centre of the chart. In this manner the arm is securely guided with regard to the centre of the diagram, if the tracing pin is set to the point of commencement of the registered curve, and traces the whole curve from left to right. Following the radius to or from the

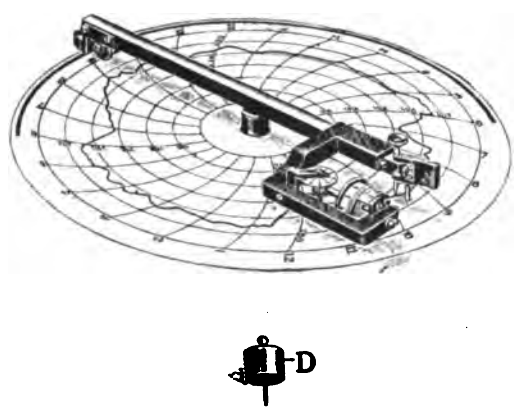



FIG. 60.

centre to the same distance as that of the starting-point, the reading multiplied by a constant denotes in inches the mean radius of the diagram, if the registration is exactly one round of the chart. If it is less or greater, the obtained reading of the roller must be reduced to one revolution. If, for instance, the time of registration is only sixteen hours, then the reading must be multiplied by 24/16. The ordinates may be straight or curved provided they have equidistant intervals.

The Radial Averaging Instrument possesses a few specially interesting features, not only from a practical but also from a theoretical point of view. If we denote by $r$ and $\phi$ the polar co-ordinates of the curve traced, then the measure of turning, $\theta$, of the circumference of the integrating roller is defined by the equations

$$\theta = \int_{\phi_1}^{\phi_2} r d\phi \quad \text{or} \quad \theta = \int_{r_1}^{r_2} r \frac{\phi d}{dr} dr.$$

With certain algebraic curves, such as straight lines, circles, ellipses, etc., the above integrals lead to hyperbolic, cyclometric, and elliptic functions which, with the aid of this instrument, may be determined in a purely mechanical way.

The relation between the turning of the roller and the *area* defined by the tracing of the point is somewhat complex, but it can be derived in the following manner. We have

$$\theta = \int r d\phi = \int \int d r d\phi = \int \int \frac{r d r d\phi}{r} = \int \frac{df}{r}.$$

In consequence thereof $\theta$ is equal to the sum of quotients of the single elements of area $df$ by their relative distances $r$ from the centre of measurement, or, put differently, $\theta$ is equal to the potential of the area enclosed by the curve (the density of mass supposed to be unity) about this centre.

### HATCHET OR PRYTZ PLANIMETER

Prytz, of Copenhagen, has designed a planimeter which although simplicity itself in construction has a rather complicated theory. The instrument consists of a metal arm $A\,B$, bent at right angles at both ends, as in Fig. 61. The end $B$ is in the form of a knife edge or hatchet, while $A$ is the tracer. It is clear that $B$ can only move freely along the line $A\,B$, and thus when $A$ is made to describe the given curve, the point $B$ traces a curve such that $A\,B$ is always tangent to it. The theory of the instrument is as follows: If the arm of constant length $A\,B$ (Fig. 62) be always tangent to the curve $C$, then $\acute{a}$ is zero for all positions, and it is seen that the elementary area swept out by $A\,B$ is $\frac{1}{2}l^2 d\phi$, and thus the total area swept out is given by $\frac{1}{2}l^2 \int d\phi = \frac{1}{2}l^2\phi$ where $\phi$ is the

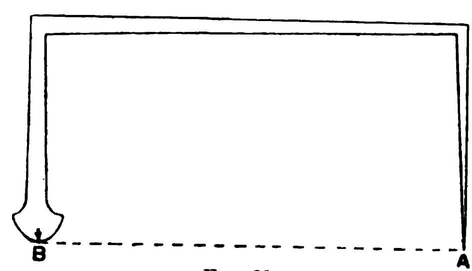


FIG. 61.

angle turned through by the arm in making a complete circuit of the curve. The area swept out by the arm is made up of the required area $S$ of the curve $C$, and the area (which will be described in the opposite sense) between the curve $C^1$ and the initial and final positions of the arm $A\,B$. This latter area can be shown to be approximately $\frac{1}{2}l^2\phi$ if the

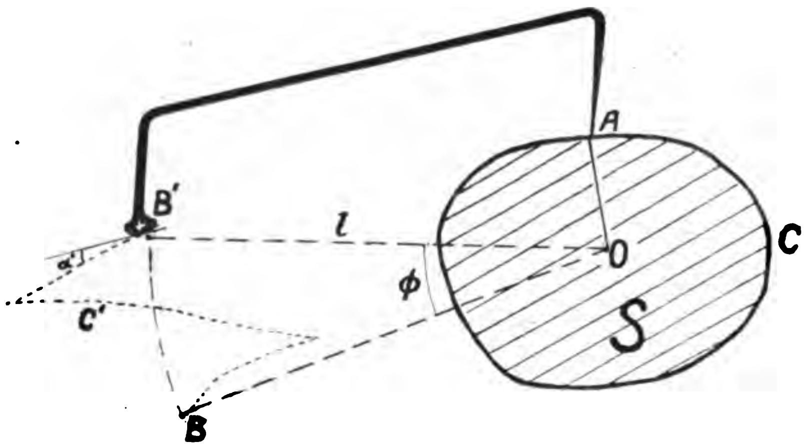



FIG. 62.

normal to $A\,B$ at $A$, in its initial position, divides the curve into two nearly equal portions

$$\therefore\ S-\frac{1}{2}l^2\phi=\frac{1}{2}l^2\phi$$

$$\text{i.e. } S=l^2\phi.$$

Hence, if $A\,B$, $A\,B^1$ be the initial and final positions of the arm, the required area is equal to the product of $l$ and the length of the arc $BB^1$ of the circle whose centre is $A$ and radius $l$. In Prytz's own theory of the instrument he starts the tracer at a point $O$ interior to the area to be measured, moves it along a radius vector, makes a complete circuit of the curve, and returns to the point $O$ by the same radius vector, and he shows that if $O$ be approximately the centre of gravity of the area, the area required is given approximately by $l^2\phi$ as above.

Within limits the chord can be measured instead of the arc $l\phi$ if $O$ be near the centre of gravity.

In Goodman's form of Prytz's instrument a part of the arm is bent into a graduated circular arc of radius $l$. This enables the required area to be got by measuring the arc $BB^1$ by means of this scale, and the scale is calibrated so as to give the reading in units of area. Kriloff has substituted a sharp edged wheel for the knife edge, and claims greater accuracy in the results obtained.

Another instrument which, like Prytz's, has the peculiarity of not having an integrating wheel, is the planimeter of Petersen. In this the arm of constant length is constrained to move, always keeping parallel to a fixed direction. A still further modification is to construct the instrument with the distance $A\,B$ adjustable, then if $A\,B$ is set to the width of the diagram the distance between the initial and final position of the knife edge gives at once the mean ordinate. This is specially applicable to indicator diagrams, but the accuracy is questionable, as Prytz states in his original description that $A\,B$ should be about twice the width of the area.

### Linear Planimeters

In a large class of planimeter, especially the more complicated double integrator type, the radius arm is replaced by a straight guide bar or rollers forming the equivalent of this bar.

The theory of these instruments is simpler than that of the polar type and can be developed from that already given by considering the

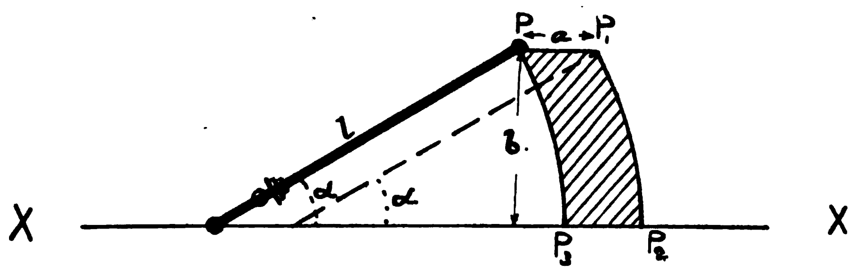



Fig. 63.

polar arm as infinite in length, or more readily by considering the above diagram.

Let the shaded portion (Fig. 63) represent the figure $P\,P_1\,P_2\,P_3$ the area of which is obviously equal to $a\,b$.

The planimeter arm of length $l$ is constrained to move along the line $X\,X$. If the tracing point is taken round the diagram, clockwise, the reading from $P$ to $P_1$ will be equal to $k\,a\sin\alpha$; where $k$ is some constant

From $P_1$ to $P = C$ say.

From $P_2$ to $P_3$=zero (the motion of the wheel being entirely slipping).

From $P_3$ to $P = -C$ which cancels out the reading from $P_1$ to $P$.

Thus the only reading indicated is $k\,a\sin\alpha$.

Now $\sin a = \frac{b}{l}$

therefore the area $= \frac{k}{l} a\, b$.

If $\frac{k}{l}$ is made equal to unity in any appropriate system of units the recording wheel will read area directly.

An example of a very simple linear planimeter is shown in Fig. 64;

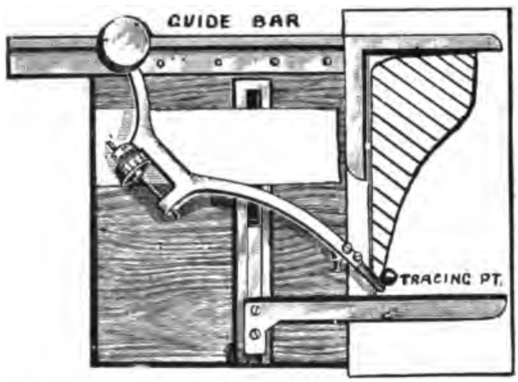



FIG. 64.

this is known as the "Coffin" planimeter and is specially adapted for indicator diagrams.

Fig. 65 shows a more generally useful form fitted with a roller $A$ milled at each end to prevent slipping. This roller is pivoted in the

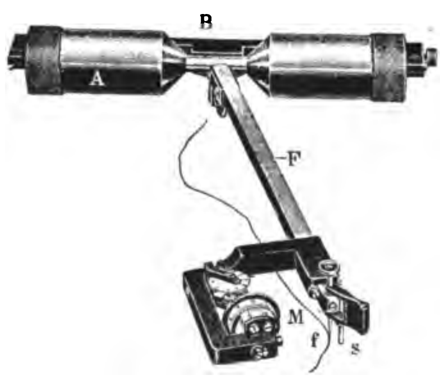



FIG. 65.

frame $B$ to which the tracer arm $F$ is hinged. The recording wheel is of the usual form, as shown at $M$.

A more elaborate instrument of the same type is shown in Fig. 66, which also rolls on the diagram, but has a disc on which the recording wheel

works. The rollers $R^1$ $R^2$ are rigidly connected through the spindle $A$ and rotate the disc $S$ by means of gears. The recording wheel $R$ is carried in a frame $M$ which is hinged at $d$ in the horizontal plane, but constrained to turn about a vertical axis with the frame $H$ which carries the tracer arm $E$. A great advantage of this type of instrument is the fact that

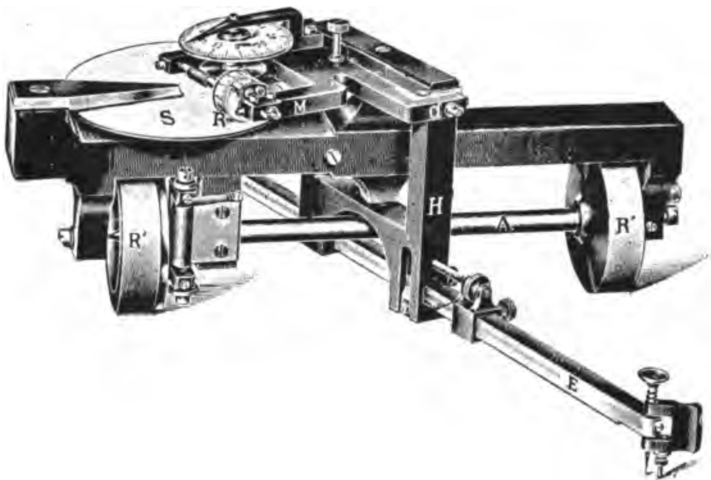



FIG. 66.

it is capable of evaluating a long narrow area. By a complicated arrangement of mechanism the area of a diagram with curved ordinates such as continuous instrument charts can be obtained, and also mean ordinates of these charts with non-uniform scale of deflection, but these appliances are only used in very special cases and are too expensive for general work.

## MOMENT PLANIMETERS

The moment of an area, and its moment of inertia about a given line may be obtained mechanically upon similar principles to those by which a simple area is obtained.

If $A$ $B$ $C$ $D$ $E$, Fig. 51, be the figure whose moment of area and moment of inertia are required about any line $O$ $X$, then, taking any element of area $A$ $B$, if $y$=height of upper portion $S$ $B$, then the moment of area of the element $S$ $B$ about $O$ $X$ is

$$m = \text{area of } S\,B \times \frac{y}{2}$$

$$= \frac{1}{2} y_1{}^2 \triangle x.$$

Similarly the moment of inertia of the element is

$$i = \frac{1}{3} y_1{}^3 \triangle x.$$

The sum of an infinite number of such expressions as these, when $\Delta x$ becomes infinitely small, gives respectively the moment of area and moment of inertia of the whole figure according to the expressions

$$\text{Moment of area } = M = \frac{1}{2}\int y^2 dx$$

$$\text{Moment of inertia} = I = \frac{1}{3}\int y^3 dx.$$

Now it is possible to obtain these results mechanically by causing the measuring roller to be directly turned at a rate which is made to vary, not as in the simple planimeter with the value of the ordinate ($y$), but with its second or third power. Though no method of directly doing this

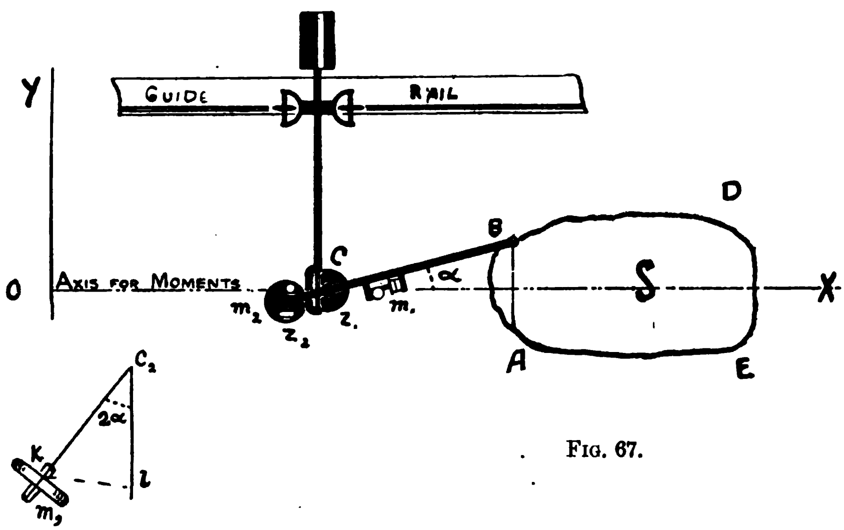



FIG. 67.

has apparently yet been suggested, yet the same result is practically effected by the very simple application of a mathematical principle in the Amsler "Moment Integrator."

Let the pole arm $CB$ (Fig. 67) be attached to a toothed segment $Z_2$ which gears with a toothed wheel $Z_1$; the effective radius being as 1 is to 2.[1]

Let the centre $C$ of $Z_1$ be carried along $O\,X$.

Let $m^2$ be a recording drum, acting in every way as the measuring roller of the Amsler planimeter, whose axis is carried in the plane of the wheel $Z_2$.

When the pole arm coincides with $O\,X$, let the plane of rotation of the

[1] By this ingenious arrangement of mechanical parts the same result is obtained by the use of two equal wheels as if the pole arm $CB$ carried a quadrant of twice the radius of the wheel $Z_2$ and $Z_2$ turned about an axis fixed to the frame.

roller $m_2$ be parallel to $O X$ and its axis parallel to $O Y$. When the pole arm is turned through an angle $S C B=a$, the angular motion of the wheel $Z_2$ is twice that of the arm; thus the roller $m_2$ takes the position shown in figure.

This is so because $\dfrac{< r \text{ motion of } Z_2}{< r \text{ motion of } Z_1}=\dfrac{\text{radius of } Z_1}{\text{radius of } Z_2}=\dfrac{2}{1}.$

$$\therefore \; < kc_2l=2a.$$

Suppose the tracing point $p$ to move through the width of the element $S B$ at a height$=y$, and with it $Z_1$ and $Z_2$, the roller $m_2$ being in contact with the diagram surface.

Then $\dfrac{\text{Turning of } m_2}{\text{Motion of translation of } m_2}=\dfrac{2\pi r n_2}{\triangle x}=\dfrac{lc_2}{c_2k}.$

Where $r$=radius of roller and $r_2$=reading

$$=\cos 2a$$

$$=1-2\sin^2 a$$

but $\dfrac{SB}{CB}=\dfrac{y_1}{R_1}=\sin a$

(where $CB=R_1$)

$$\therefore \frac{2\pi r n_2}{\triangle x}=1-2\sin^2 a$$

$$=1-\frac{2}{R_1^2}y_1^2$$

or $$n_2=\left(\frac{1}{2\pi r}\right)\triangle x-\left(\frac{2}{2\pi r R_1^2}\right)y^2\triangle x.$$

When the perimeter of the curve has been traversed, the sum of a series of quantities similar to the first becomes zero; so that by making the constant $\left(\dfrac{1}{\pi r R_1^2}\right)$ equal to $\dfrac{1}{2}$ the reading of the roller gives the value

$$M=\frac{1}{2}\int ydx$$

or the moment of area of the figure $B D E A$, about $O X$ from which the centre of gravity can easily be obtained.

Fig. 68 gives an illustration of the instrument as generally constructed, the pole arm being provided with an additional recording drum to measure areas in the same way as the linear planimeter. The instrument moves along the guide bar on two wheels, and a counter balance weight is fitted to reduce the pressure on the recording wheels. For determining the moment of inertia of an area a similar instrument, shown in Fig. 69, is used. This has a segment of $C$, the radius of which is three times that of

another wheel $Z_3$, with which it gears. The action of the roller $m_3$, carried by the wheel $Z_3$, is exactly the same as that of $m_2$ (Fig. 67), except that its angular motion is three times as great as the pole arm $CB$ instead of twice as great as in the case of the other roller.

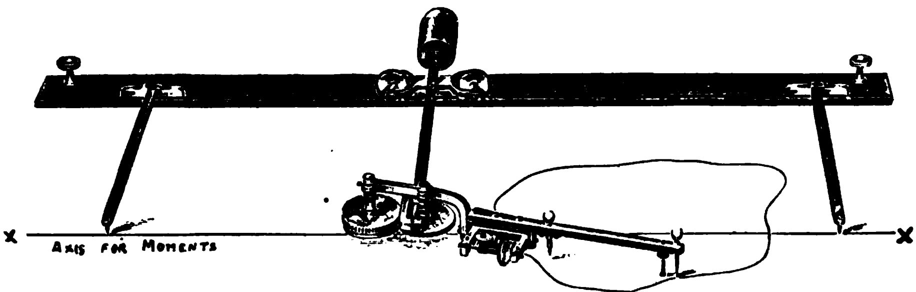



FIG. 68.

By reasoning similar to that already adopted, and taking the plane of rotation of $m_3$ perpendicular to $O\,X$ in its initial position, instead of parallel to it, as in the former case.

$$\text{Then } \frac{\text{Turning of } m_3}{\text{Motion of translation of } m_3}=\frac{2\pi r n_3}{\triangle x}=\frac{2^1C_3}{C_3K}$$

$$=\sin 3a$$

$$=3\sin a-4\sin{}^3 a.$$

but
$$\frac{SB}{CB}=\frac{y_1}{R}=\sin a.$$

Therefore
$$\frac{2\pi r n_3}{\triangle x}=3\sin a-4\sin^3 a$$

$$=\frac{3y_1}{R_1}-\frac{4y^3}{R_1{}^3}$$

or
$$n_3=\left(\frac{3}{2\pi rR_1}\right)y_1\triangle x-\left(\frac{4}{2\pi rR_1{}^3}\right)y^3\triangle x$$

which, when the pointer is taken round the curve, gives, with suitable values of the constants

$$n^3=\int ydx-\frac{1}{3}\int y^3dx.$$

$$=\text{area of } B\,D\,E\,A-\text{moment of inertia of } B\,D\,E\,A.$$

$$=A-I$$

or
$$I=A-n^3$$

The instrument has an area planimeter roller on the pole arm, and by reading the rollers $m_1$ and $m_3$ and subtracting the results, the moment of inertia is obtained about the axis $OX$.

The complete instrument is shown in Fig. 70. The instrument also serves as a moment of area planimeter, and as already stated an area planimeter. The addition of another segment and wheel having a ratio

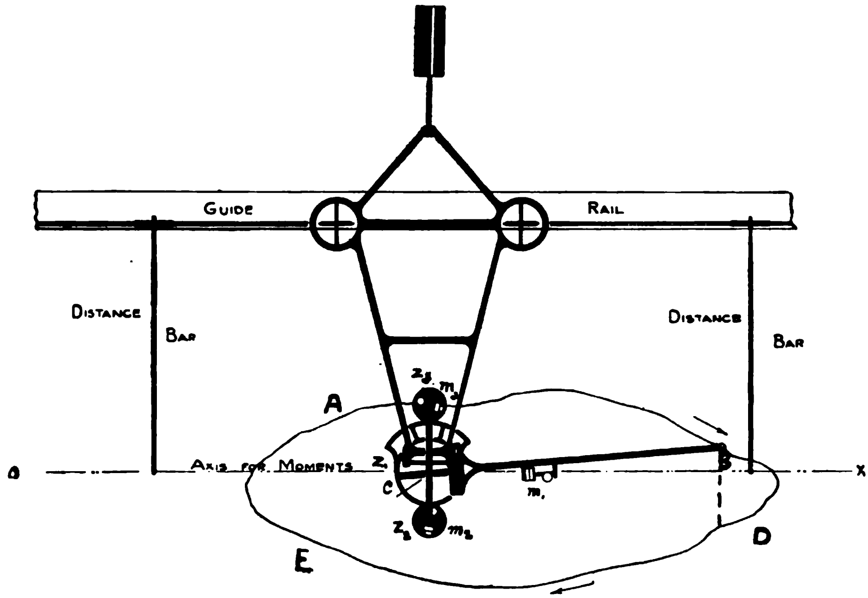



FIG. 69.

of 4 to 1 will provide a means of measuring moments of the fourth order and the construction of an instrument to measure area, moment of area, moment of inertia, and fourth moment about an axis is shown in Fig. 71.

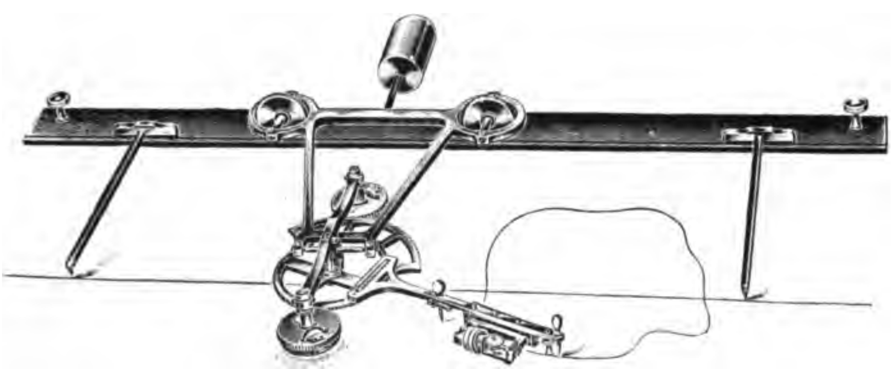


FIG. 70.

In all designs of planimeters employing recording wheels rolling on the diagram, the motion of the wheel consists partly of slipping and partly of rolling. Consider the wheel in Fig. 72. The motion of this wheel in going from $A$ to $B$ can be regarded as entirely slipping perpendicular

to its own plane along the line $A\,C$, and then rolling from $C$ to $B$; the slipping must always take place to a more or less extent and eventually wears slight flats on the wheel which affect the accuracy. Attempts have therefore been made to render the motion entirely rolling without

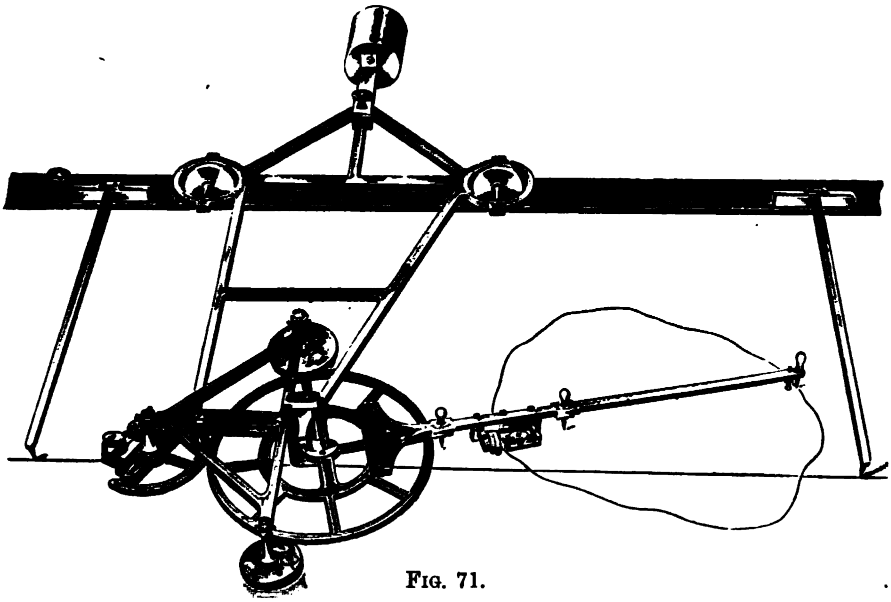


FIG. 71.

slipping, and the disc types already shown partly effect this purpose. Another scheme is to employ spheres and arrange the recording wheel to swing around on a generating line. The velocity ratio of the sphere and wheel in Fig. 73 will vary in proportion to $r$, the diameter of the

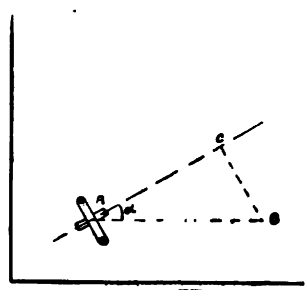


FIG. 72.

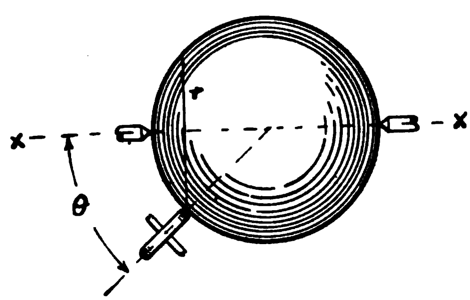



FIG. 73.

measuring roller being fixed or as $R$ sin $a$. The only slipping is that which occurs during the change in $a$. This could be eliminated by using a cylinder which rolled on a generating line during the change in $a$, as suggested by Amsler, but the instrument is too complicated mechanically to justify its construction.

A very neat example of an integrator using spheres has been designed by Prof. Hele Shaw, and is shown in Fig. 74. The three glass spheres derive their angular rotation from the rollers resting on the diagram, and each sphere is supported by small wheels, as shown. The recording rollers are attached to the upper framework and rotate about a vertical

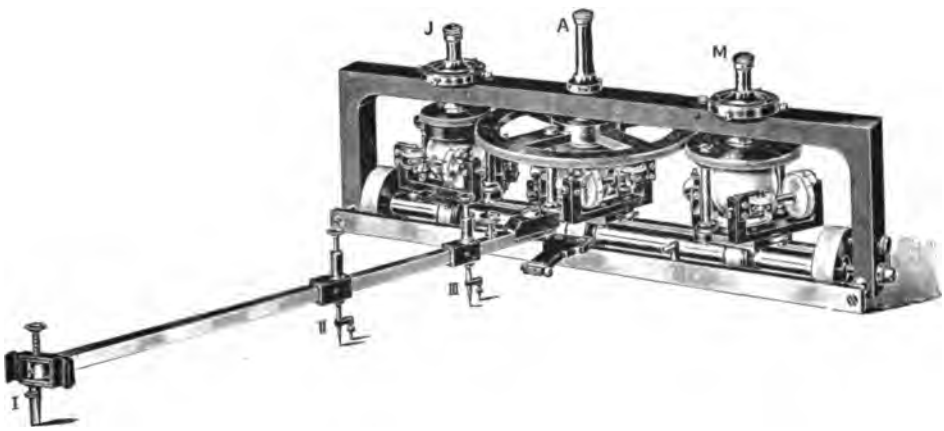



FIG. 74.

axis. The recording wheels measure, under $A$ area, under $M$ moment of area, and under $J$ moment of inertia of the area. Three tracing points are provided along the pole arm for various scales to suit small or large diagrams.

### ACCURACY OF PLANIMETERS

Very extensive series of experiments have been carried out by different observers on the errors of various types of planimeters. Amsler found that with a disc type instrument, after making successive series of 8 revolutions of the disc corresponding to 130 revolutions of the measuring roller the difference in the ratio of the readings of the disc and roller in the second 8 revolutions in the worst case amounted to $-0{\cdot}0003$ and generally was less than $+0{\cdot}000001$.

For the case of the polar planimeter, he found the maximum error occurred when the axis of the wheel was at about 45° to direction of motion, and was then about 1 in 1000 of the reading calculated, but in general the error was much less than this.

Prof. Tinter formed the conclusion by examining nine different planimeters, that the angle of the measuring roller had very little effect, but agreed with the previous paragraph in estimating the error as from 0·00075 to 0·0013 dependent upon the fact as to whether the centre of rotation was within or without the area. Finally, Prof. Lorber, from

very elaborate and extensive experiments, concludes that the error in the reading is represented by

$$dn = K + u\sqrt{n},$$

$dn$ = the error in the reading. $K$ and $u$ being constants and $n$ = reading the measuring roller.

Or

$$dFn = Kf + u\sqrt{Ff}$$

where $F$ = actual area to be measured

$dFn$ = the error in the result in terms of $F$ the area.

The following are some of his results.

Polar planimeter $dF = 0{\cdot}00126f + 0{\cdot}00022\sqrt{Ff}$

Linear planimeter $= 00081f \ +0{\cdot}00087\sqrt{Ff}$

Rolling planimeter $= 0{\cdot}0009f \ +0{\cdot}0006 \ \sqrt{Ff}$

It is evident that under the best conditions the accuracy of the planimeter is very high, probably greater than the accuracy of the diagram. But it must be borne in mind that friction at the pivots and maladjustment will very materially influence the accuracy under ordinary conditions of working.

## REFERENCES

"Ueber das Roll-planimeter von Coradi." Von Franz Lorber. *Zeitschrift des Oesterreichischen Ingenieur—und Architekten—Vereins*, Vol. XXXVI., p. 135.

Hele Shaw, "Mechanical Integrators," *Min. of Proc. of Instit. Civil Engineers*, 1885, p. 75.

Hele Shaw, "The Theory of Continuous Calculating Machines and of a Mechanism of this class on a New Principle." *Phil. Trans. Roy. Soc.*, Vol. CLXXVI., Part II, p. 367. 1885.

*Modern Instruments and Methods of Calculation.* Handbook of the Napier Tercentenary Exhibition.

Derselbe, "Ueber Mechanische Integrationen," im *Katalog math. und math-phys. Modelle, Apparate und Instrumente.* Herausgegeben von W. Dyck, Mü chen, 1892.

A. Russel and H. H. Powles, "A New Integrator," *The Engineer.* 1896.

Henrici, "Report on Planimeters," *British Association Report*, p. 496, 1894.

Bramwell, "Amsler's Planimeter Report." *B.A.*, 18 2, p. 40.

# CHAPTER IV

## THE MEASUREMENT OF VOLUME

OWING to the great practical importance of volume measurements in the sale of commodities such as coal gas, and water, as well as for the control of industrial operations, much thought and labour has been expended on the development of appliances to meet the most diverse requirements. Whilst the various meters differ fundamentally in mechanical details, it is possible to group them into three distinct classes, according to the basic principle of operation.

1. The displacement or positive type in which a chamber is charged and discharged alternately.
2. The continuous-flow type which involves the measurement of the velocity of the stream and a mechanism for integrating the flow over a time interval.
3. Miscellaneous instruments, utilising some thermal property of the fluid and suitable electrical devices for recording such changes.

## SECTION I

### (a) PISTON TYPE WATER METERS

The vast majority of liquid meters are designed for the measurement of water; but as the term " water " is fairly elastic and embraces liquids varying from nearly chemically pure $H_2O$ to a mixture of sand and water, it will be realised that any one form of meter will not be equally adapted for all requirements. For the measurement of domestic water supply the chief requirement is automatic action and reliability. The meter must be capable of insertion in the pipe-line under pressure and not absorb much head for its operation. Positive type meters are in very general use for this class of work.

*The Kennedy Meter.*—One of the oldest of this class is the Kennedy

meter, invented by Thomas Kennedy, in 1852, and shown in Fig. 75. In the cold-water meter the vertical measuring cylinder is provided with a piston kept tight by a rubber ring, which rolls between the surface of the cylinder and the bottom of the wide grove in the piston, so avoiding sliding friction.[1] The upper end of the piston rod is provided with a rack which rotates a pinion connected with the counter, and also operates the valve gear. The pinion carries an arm which catches the haft of a swinging hammer; the arm lifts the hammer until it has passed its dead centre, when the hammer falls over by gravity and strikes a finger connected with the valve gear and so reverses the motion of the piston, and similarly on the return stroke. The swinging hammer prevents the valve from stopping in its mid position. A buffer is provided which absorbs any surplus energy in the hammer which comes to rest with a thud.

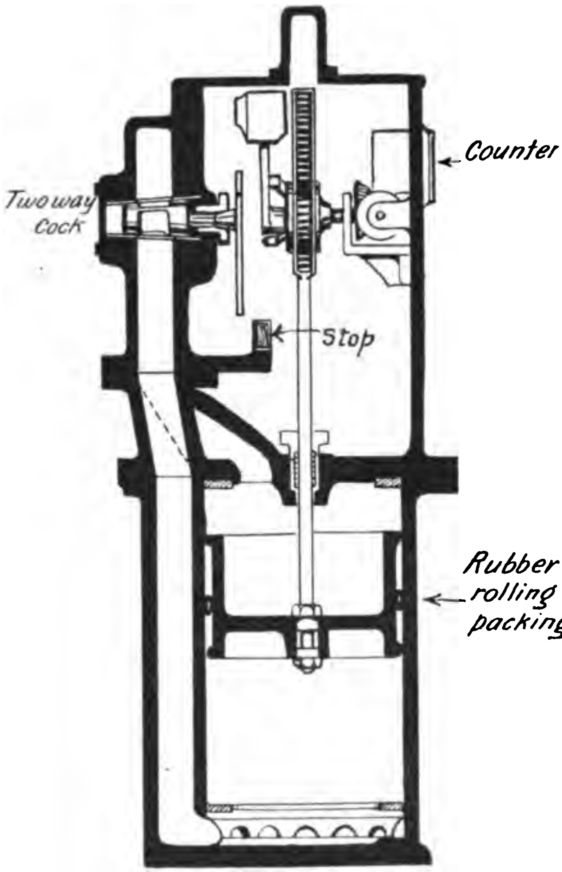



Fig. 75. Section of Cold Water Meter

It will be observed that the indicating mechanism measures the length of the stroke, and not the number of reciprocations. This is important, because the travel of the piston is subject to accidental variations, due to speed of working, friction, etc. By means of a double ratchet, operating through the little bevels, the length of the stroke is measured continuously during both the up and down motions of the pistons. If it is desired to record the rate of flow with the piston and cylinder type of meter, which is essentially an integrating meter, it becomes necessary to introduce a clock and drum, by means of which

[1] In the same way as that employed in the air brake of railway carriages.

the number of operations in unit time are recorded or shown. This is effected in the Kennedy meter as follows: The recording arrangement (Fig. 76) consists of a crank $A$, driven from the index gearing, and connected by means of a connecting rod $B$ to a vertical sliding bar $C$. The gearing is so arranged that the crank, and therefore the sliding bar, makes one complete up and down motion for, say, 200 gallons, and a line is thus drawn on the diagram $E$, which is wound round the drum of the clock, a pencil being mounted on the lower end of the sliding bar.

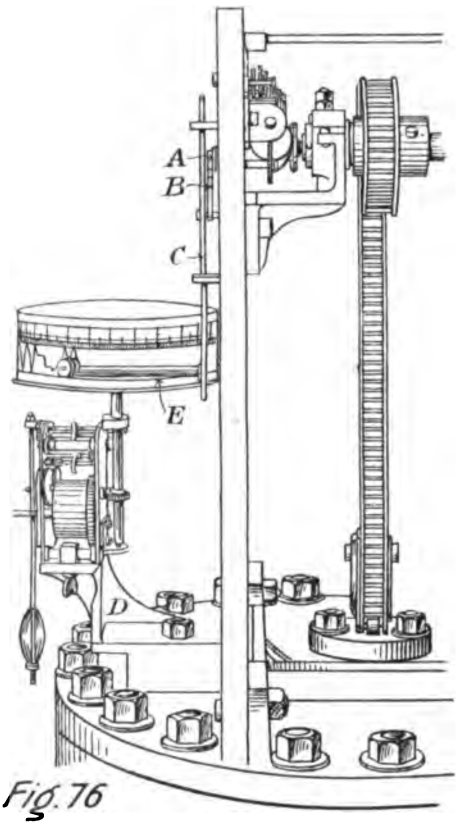


Fig. 76

RECORDING MECHANISM ATTACHED TO AN INTEGRATING TYPE OF METER (KENNEDY).

*The Frost Meter.*—Another form of piston and cylinder meter, which is in extensive use, is shown in Fig. 77. This meter was patented by Messrs. Chadwick and Frost in 1857. It consists of a vertical cylinder, fitted with a cup-leather piston. The piston rod extends upward into a valve chest and is provided with two tappets for moving the valve gear, and also with a pawl for rotating the counter. The valve gear consists of two horizontal slide valves one above the other. The upper or auxiliary valve is moved by the tappets on the piston rod through a bell-crank lever and lets water to and from two small cylinders that contain pistons attached to the lower or main slide valve, which thus distributes the water to the large measuring cylinder below.

*Worthington Piston Meter.*—Another meter of the same class, but differing radically in mechanical details, is the Worthington Piston Meter. This meter has been designed primarily for use in connection with boiler plants—the feed-water supply being an indication of the stream generating capacity of the boiler at any time. The illustration below (Fig. 78) shows the detailed construction which in general design is similar to that of the ordinary duplex double-acting pump.

There are two cylinders, in each of which a plunger moves backward and forward through bronze linings, carrying a slide valve over ports in the bottom of the meter. Through these ports the chambers at either end of the plungers are alternately placed in communication with the inlet and discharge openings. Each of the plungers imparts a reciprocating motion to the lever, shown near the top of the main casing, which

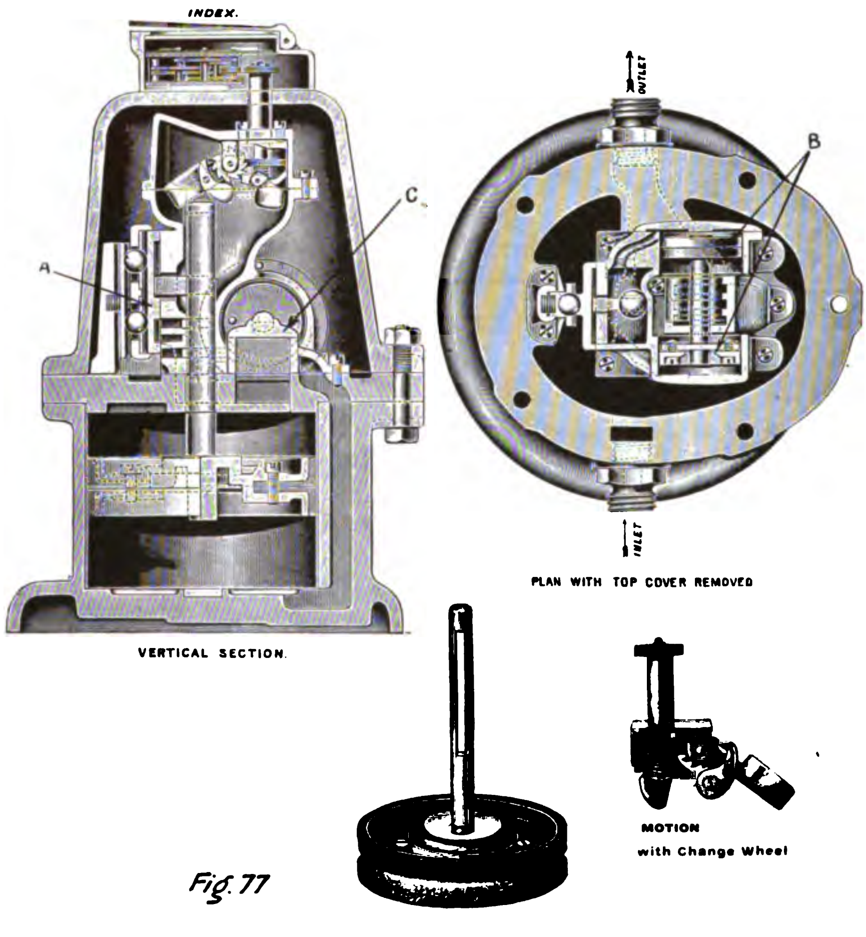



Fig. 77

in turn operates the counter movement through the spindle and ratchet, as shown. Thus it will be seen that the counter is arranged to move the dial pointers once for every four strokes of the plungers.

The counter is read in the same way as the counter of an ordinary gas meter. When a pointer is between two figures the smaller must be taken, as it is obvious that the pointer is travelling towards the larger figure and has not reached it.

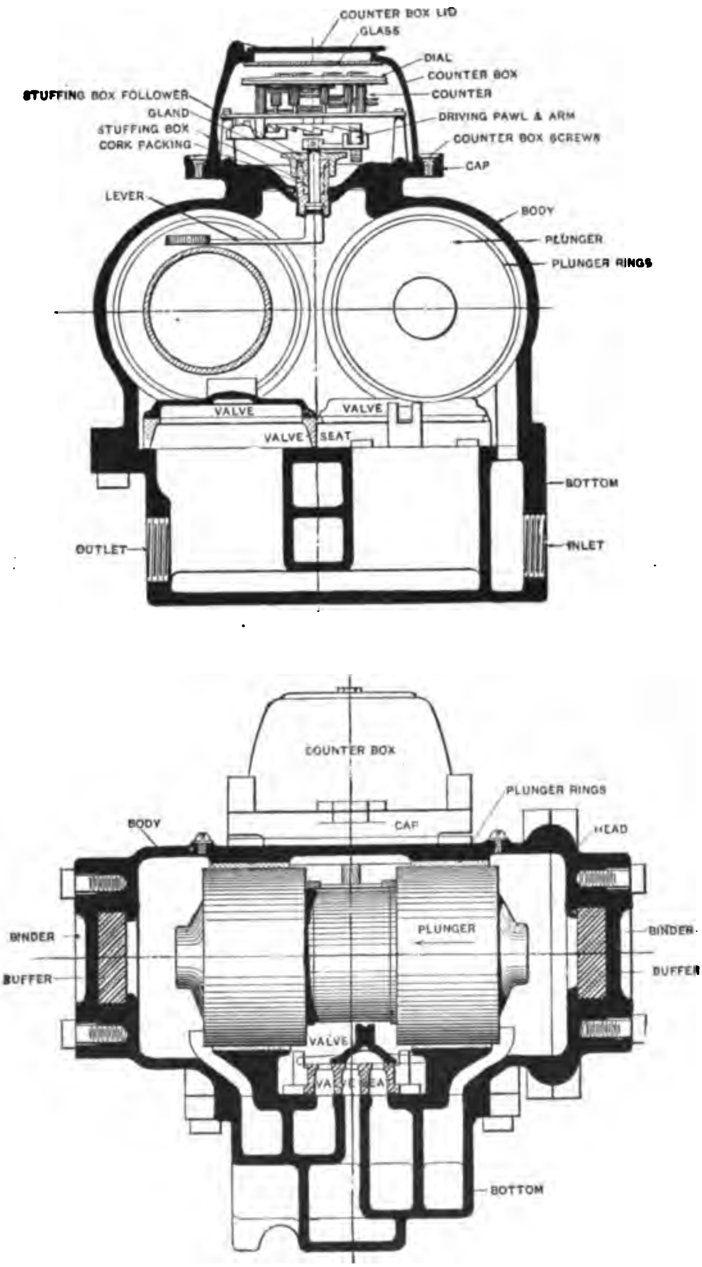



*Fig. 78 Duplex Piston Meter*

*Nutating Piston Meter.*— This displacement meter is of novel mechanical construction and has the advantage of extreme simplicity. Consequently it is frequently used for metering the water supply to small consumers. The complete meter is illustrated in Fig. 79, whilst Fig. 80 is an enlarged view of the disc and casing. The disc of vulcanite is mounted on a ball working in sockets at the top and bottom of the chamber and just touches the sides of the chamber all the way round, dividing it into an upper and lower compartment. On one side is a thin partition extending half-way across and passing through a slot in the disc. The disc does not rotate, but has a motion similar to that of a coin which has been spun on edge and is coming to rest, tilting around its edge.

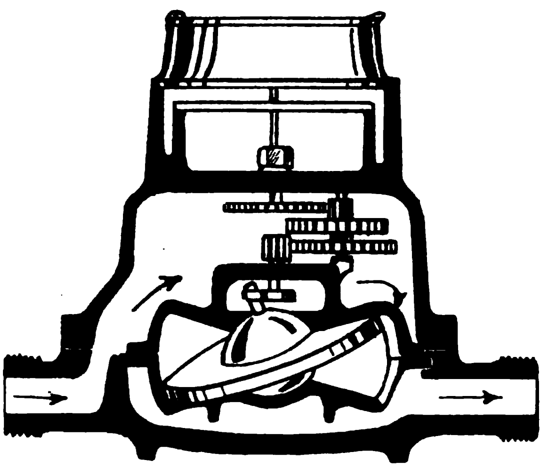


Fig 79

In the position shown in Fig. 79 the water will enter from above, as indicated by arrow at one side of the partition (shown at the right in Fig. 79), flow under the disc, tilting the back edge of the disc upward as it moves around and the opposite edge downward, forcing water out through the lower opening at the rear side of the partition, as shown by the arrow. Water enters above the disc in a similar manner: while one compartment is filling another is emptying, making the flow continuous. The end of the spindle projecting upward from the disc is given a circular motion. In revolving it pushes around a little lever attached to the spindle of the gears in the middle compartment, which in turn move the hands on the register dial. Each complete movement corresponds to filling the measuring chamber once. The number of times this is done is recorded by the dials.

*Disadvantages of the Piston Type Meter.*—Although the displacement type meters are theoretically the most accurate there are serious practical disadvantages if the water is not free from solid matter, such as sand, etc., on account of the friction and wear of the closely fitting ports, and this defect is especially noticeable with the nutating piston form, which has no packing on the piston.

*Testing of Piston Type Water Meters.*—Any meter used in connection with a steam plant or other installation where accuracy is desired, should have a complete by-pass arrangement so that it can be periodically tested and quickly cut out in case of emergency. It is most desirable to arrange the meter so that it can be tested for accuracy without much trouble. Bearing in mind the liability to error of all types of water meters it is of little use regarding them as instruments of precision, and having no method of checking their accuracy.

With the meter in the circuit under pressure the most convenient arrangement for testing is to have a special by-pass arrangement connected to a calibrated tank of 500 to 1000 gallons capacity, which has been calibrated by weighing and corrected for temperature. It is advisable in the case of pressure meters to install a back-pressure valve to equalise the action of the boiler feed pump. When calibrating a meter of large size on a small quantity of water it is to be remembered that in some forms the counter moves only once for each complete revolution of the plungers; that is, the plunger must make one stroke forward and one stroke back before the counter moves once. Hence it is essential that the plungers should be started and stopped in the same relative position.

Fig 80

*Automatic Volume Measuring Meters.*—Besides the above described piston meters there are others of the displacement type in which the water is metered by charging and discharging a tank of known volume automatically. In the Tippler meter there are a pair of tanks each fitted with a float and valve. The water is directed into either tank by a light shoot mounted on knife edges.

The mode of working of the meter may be briefly described as follows: The shoot directs the water to be measured into one tank and when the level has risen to a certain height the float comes into operation and rises. This throws over a weight, tips the shoot so that the water is now discharged into the other tank, opens the outlet valve and drains

the full tank. The same set of operations is repeated by similar mechanism in the other tank.

In the working of these meters care has to be taken to keep the valves in good order, and for accurate work it is advisable to fit a gauge-glass and scale to check the volume at the instant of tipping.

*Automatic Weighing Meters.*—Meters in which the water is weighed are also in use. The general scheme of one form is to mount the tank on trunnions so arranged that the tank overbalances when it contains a certain weight of water. The overturning is utilised to bring another tank into action while the former is emptying.

In the Avery automatic liquid weigher the principle of an equal armed beam is adopted, with the weight suspended at one end, and the weigh hopper at the other. A quantity of liquid determined by the weights in the weigh box is allowed to enter the weigh hopper and when the correct amount has accumulated the supply is automatically cut off. The cutting off is done gradually, so as to bring the weight of liquid to the exact amount necessary for balance. Account is taken of the liquid in the air between the valve and the hopper. Immediately after receiving its load the weigh hopper overturns and discharges its contents. The empty hopper then returns to the weighing position again, and the same cycle of operations takes place. No external power is required to work the scale and a mechanical counter is fitted which automatically counts every weighing made. The weigh hopper is so designed that it completely discharges itself without shock, and a draining compartment prevents any residue remaining. The size of the outlet can be varied to allow thick or thin liquids to completely drain before the hopper tips back. The machine can be tested at any time without difficulty, as in the case of any ordinary weighing machine.

The essential features and method of operation of the machine will be understood from a study of Figs. 275, 276, page 265, which illustrate the automatic grain weigher, which works on the same principle.

Neither the automatic volume measuring nor the automatic weighing machines are adapted for use in circuits under pressure, but are of course of considerable service in experimental work, and automatic weighing machines are available for capacities of 20 lbs. per discharge to $2\frac{1}{2}$ tons.

### (*b*) Petrol Measuring Pumps

Measuring pumps for the retailing of petrol have found extensive application in America where the liquid is usually stored in large tanks

buried below ground level. A typical installation with measuring pump is shown diagrammatically in Fig. 81.

*Piston Pumps.*—The pumps for this purpose are generally hand operated, and are identical in principle with the ordinary piston pump.

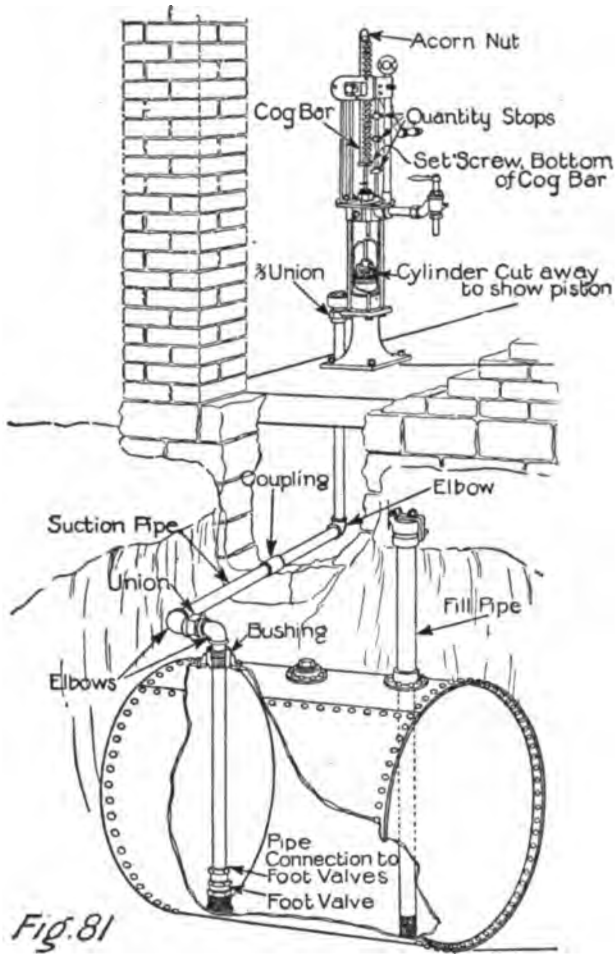



Fig. 81

*Typical piston-type measuring pump installation, showing arrangement of tank, piping, valves, etc.*

Their distinctive features are the methods adopted for defining the length of the stroke and the mechanism for ensuring that each stroke of the piston will discharge a volume of liquid equal to the volume generated by the piston in its travel. Hence it is essential in this case that there should not be any leak past the valves and packing.

The pumps vary in mechanical detail, but the one shown in Fig. 82

is typical of the class. In the case of the measurement of petrol, accuracy is the primary consideration, and as the quantities dealt with are relatively small the pumps are rarely made automatic in action.

*Overflow Type Pumps.*—Owing to the difficulty of preventing leakage in the previous type of measuring pump another system is frequently

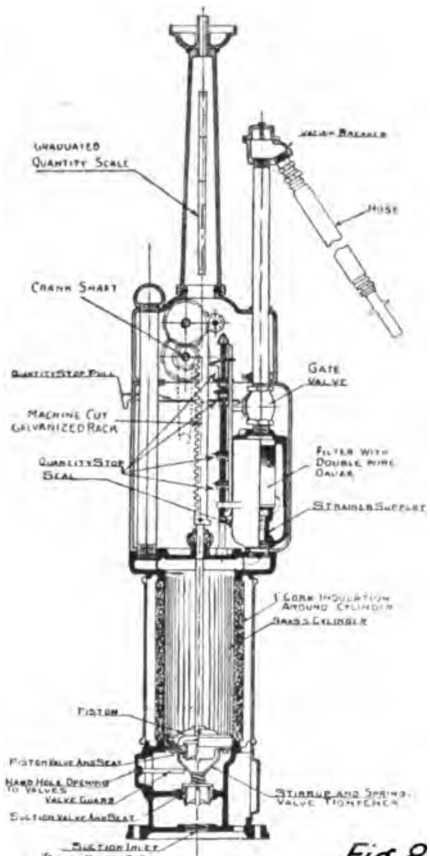
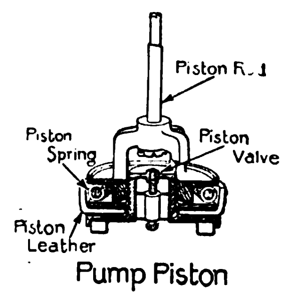


Fig. 82

*Sectional elevation of typical piston-type measuring pump*




*Section of piston, showing cup-leather, expander-spring, and lift valve*

used. In this, the function of the pump is merely to fill a vessel to overflowing, then adjusting to a definite level in the measuring vessel.

The liquid may be supplied to the chamber by air pressure; by evacuating the chamber with a vacuum pump; or by direct mechanical pumping from a supply tank.

The abstraction of excess may be performed either by gravity through an overflow pipe, or by siphoning, the height of the liquid remaining

being determined by the vertical height of the face of the orifice of such pipes above the bottom of the measuring chamber. Fig. 83 illustrates this system, while Fig. 84 is a section of a pump working on the vacuum principle.

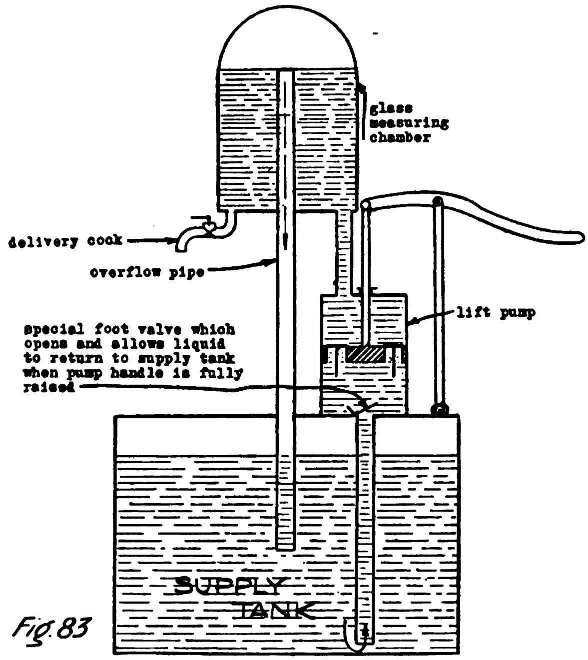



Fig. 83

*Visible measurement system, discharging excess through overflow pipe in center*

The question of the correct method of installation and inspection of petrol measuring pumps has received careful attention at the Bureau of Standards, and Figs. 81 to 84 are reproduced from a technological paper issued by the Bureau.

## (c) CONTINUOUS FLOW TYPE

In a very large class of meters the volume of the liquid flowing in a measured interval of time is obtained by passing the stream through the meter, which consists essentially either of a turbine and revolution-counting mechanism or a disc displaced by the flow and a clock-work recorder.

This type of meter is cheaper to construct than the piston and cylinder type, and is especially suitable for metering under conditions when the water is generally drawn off at full bore and then shut off entirely. Owing to leakage these meters are not very accurate, but sufficiently so

for most commercial requirements. Meters of this type are made in a variety of forms and it will suffice to describe a few of the meters in use at the present time.

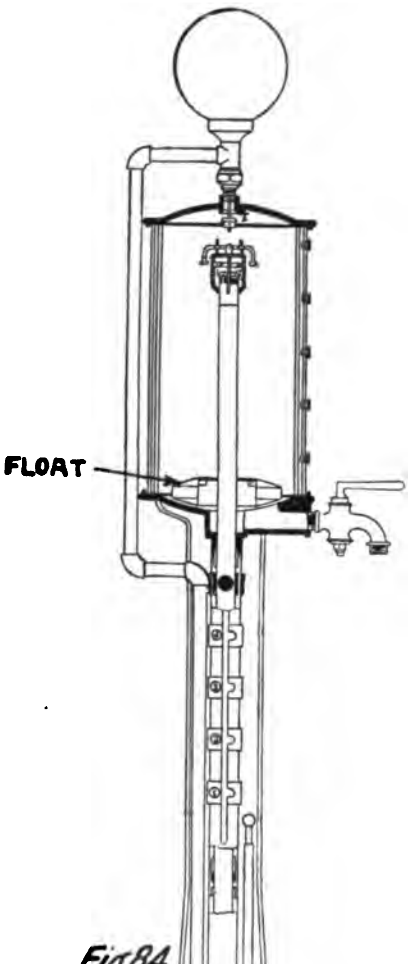



Fig. 84

Overflow type, pumping by vacuum.—*The liquid is forced into the measuring chamber from a convenient supply tank by exhaustion of the air in the chamber. The float rises and shuts off the valve. Admission of air through a two-way cock (not shown) allows the liquid in the chamber to drain back to the level of the valve seat. The central tube is adjustable to various heights by engagement with stops, allowing for various units of delivery up to the capacity of the chamber.*

*Kelvin's Integrating Meter.*—The meter (Fig. 85) is a development of that invented by Mr. G. F. Deacon for detecting and recording waste. In it a weighted disc lies in the smaller end of an inverted cone; this disc is moved vertically by the flow of water, which causes increase of the annular area between the disc and the cone, proportionate to the increase of water passing; the vertical displacement of the disc is therefore a measure of the amount of water passing through the meter. The motion of the disc is conveyed by an attached wire to a pen which records the position on a time-driven chart. Each position is calibrated in gallons per hour and the quantity shown on the diagram.

*The Integrating Mechanism.*—The method adopted by Lord Kelvin is a direct and extremely simple device (Fig. 86). He causes the meter disc to draw a counter mounted with a small vernier wheel across a centre line of a horizontal time-driven disc or plate. In the actual centre of this time-driven disc there is obviously no motion, and if the vernier wheel of the counter is resting on this centre, then no movement is transmitted to the counter. At the zero position of the meter the counter wheel is motionless and the disc is resting at the small end of the cone. When the maximum flow occurs the counter

is drawn from the centre to the periphery of the time plate, so that the maximum motion of the plate is transmitted to the counter. By this inter-connection of the disc and vernier wheel the distance of the latter from zero is proportional at any point to the amount of water passing through the meter at that position. The vernier wheel is thus enabled

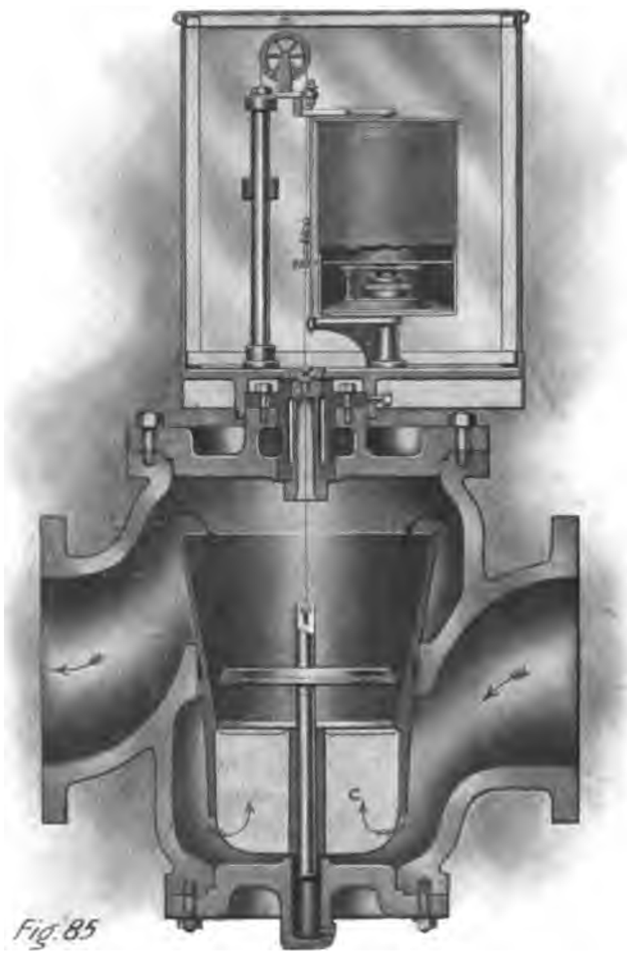


Fig. 85

to run on the time disc and totalise the amount of water which has passed through the meter for any required period. The disc movement is communicated to the vernier wheel through an ordinary fusee device, of form common in English lever and verge watches. This fusee is corrected by calibration to give the proper movement of the vernier wheel. The chief friction in the meter is between the disc wire and the

gland, which it is stated never exceeds $2\frac{1}{4}$ ozs. Added to this is the friction of flexible cords in the fusee due to bending, making another ounce—total $3\frac{1}{4}$ ounces; and it is important that this should remain constant. The makers claim an accuracy of better than 1 per cent for this meter.

*Siemens and Adamson's Meter.*—This form of inferential meter was invented by Messrs. Siemens and Adamson in 1858. The measurement is performed by a reaction wheel or Barker's mill, the revolutions of which

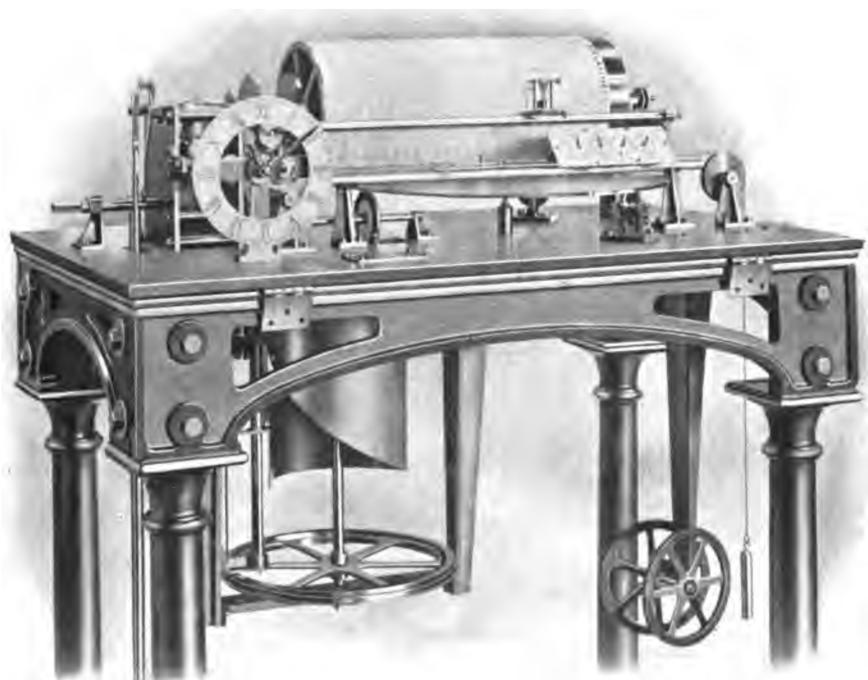


*Fig 86*

are practically proportional to the velocity of the water through the orifice. This instrument has been extensively adopted and is commonly known as the Siemens' meter.

In the sectional example shown (Fig. 87), the water before entering the casing passes through a strainer, it then reaches a fixed central pipe, down which it passes into the hollow centre of the revolving wheel, which in the example discharges it in one jet (Fig. 88). The axle of the wheel is hollow below, and rests on a pivot, while the upper end is provided with a worm which gears into the counting mechanism above.

The counter has two steps of worm gearing, as well as a differential arrangement involving a moving dial; there are two indicating fingers and a stationary pointer.

*Worthington Turbine Meter.*—The Worthington Turbine Meter is a development of the Worthington Turbine Pump. It is designed primarily

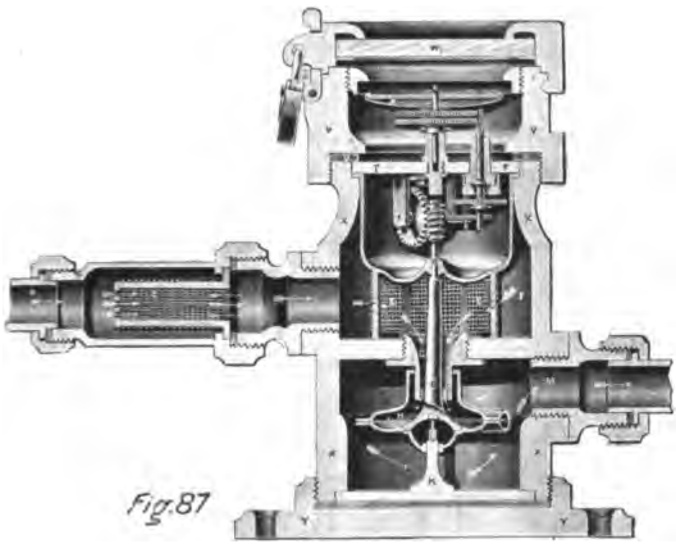


Fig. 87

to handle large volumes of water with minimum loss of head. From the sectional illustration (Fig. 89), it will be seen that the water enters the main casing through a slide strainer. The column then divides, flowing to both sides of the double wheel, which carries two sets of vanes; thus an absolute water balance is secured, and the end thrust and consequent wear which would occur if by employing only one set of vanes on the wheel is eliminated.

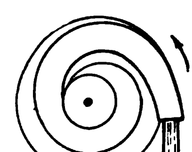


Fig 88 Impeller of Siemens & Adamson's Meter

The wheel is surrounded by a chamber of the volute pattern, providing at all points of the circumference the exact cross-sectional area necessary to handle the amount of water discharged by the wheel, at the same time conserving the speed of the water column. The wheel is of hard rubber composition, of practically the specific gravity water, and is carried on

a vertical shaft of Tobin bronze which turns on a jewelled bearing. Owing to the water balance mentioned, the friction at this point is slight, being only that due to the small excess weight of the wheel and shaft over that of the water displaced; the only parts which are subject to wear are the counter, gearing, and the bearing points.

*The Leeds Meter.*—Another form of rotary meter employed with small mains is that shown in Fig. 90 and made by the Leeds Meter Co. The interior chamber has tangential openings through which water passes in separate streams, acting on the rotary vane equally from all sides.

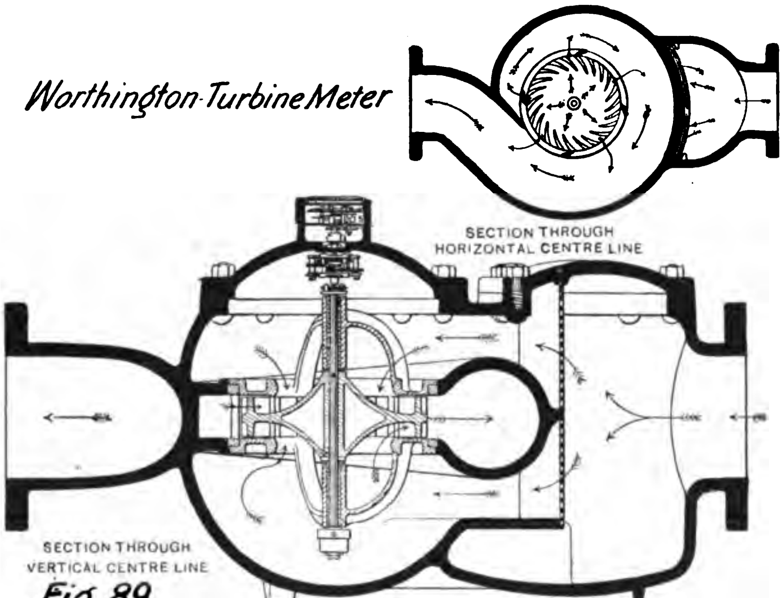



Fig. 89

The vanes are made of celluloid, which is light and unaffected by impurities in the water. In this meter the rotating vane has radial blades, and is mounted on an agate pivot; it revolves in a vertical chamber, and the water, after passing through a strainer, flows through the chamber in the form of a vortex. The speed is regulated by four adjustable vanes placed above the wheel, which act by producing eddies. The fan bearings are protected from the wearing action of the water by metal shells surrounding them. The meter has a wet dial—that is, all its mechanism is in the water; a stuffing box on the spindle, with its attendant friction, is obviated, thus making the meter more sensitive. The dial is of the transparent type invented by Mr. C. Meinecke in 1903. This consists of a thick glass plate, having the dial circles and figures formed

on its lower surface; these are covered with white enamel, in which small circular openings are left, and through these the pointers below are seen. The figures on a dial of this form cannot be obscured by dirt in the water. This meter is used for domestic and small trade supplies on mains up to about one and a half inches in diameter.

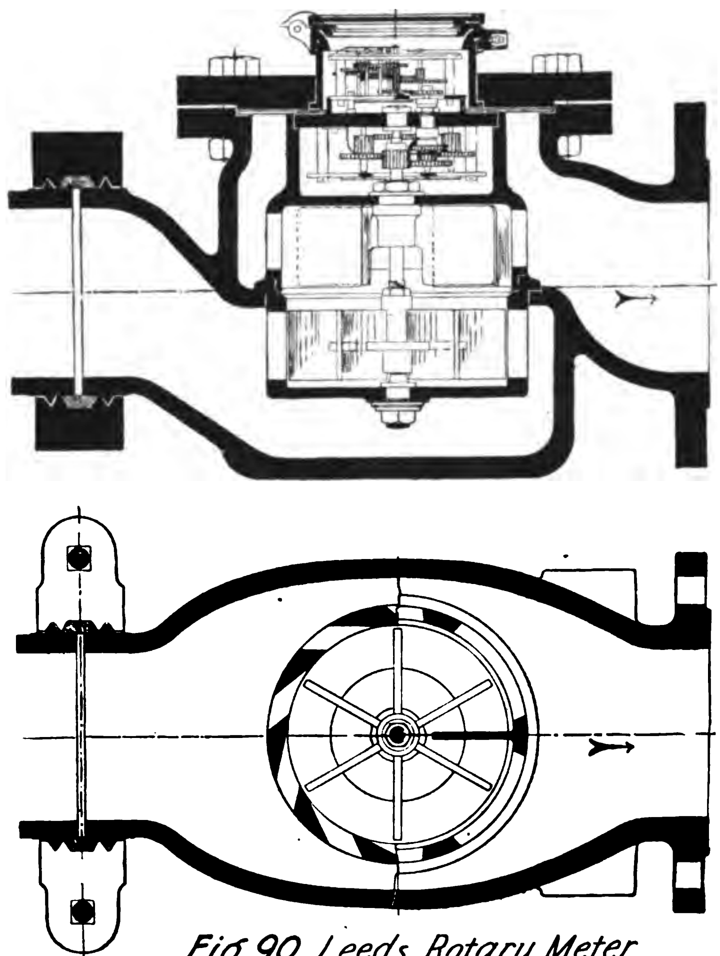


Fig. 90 Leeds Rotary Meter

*Helix Meter.*—For large supply mains a Helix type meter is frequently used, and its simple construction will be evident from Fig. 91.

*Accuracy of Water Meters used on Domestic Supply Mains.*—Water meters are commercially accurate instruments. Cases of meters which register correctly when installed and over-register after being in service are very rare. Any derangement of the meter from dirt entering the

working parts or from other causes is likely to slow the meter down and cause it to under-register. There is a small amount of unavoidable leakage through the meter which causes it to under-register when very small quantities of water are passing. Meters for measuring water for domestic use are usually graduated in cubic feet—sometimes in gallons.

Fig. 91 Helix Meter.

(d) THE VENTURI METER

One of the simplest forms of meters is the Venturi tube, and it is one which has a sound theoretical basis. Its operation is dependent on the fact that if a stream of water flows through a frictionless and horizontal pipe of varying section which it completely fills, the pressure of the water is smaller in the narrower sections and greater where the pipe is of large diameter. Since the same quantity of water flows through each cross section of the pipe, its velocity must vary inversely as the area of the pipe, and its kenetic energy will therefore be greater at these sections. As by hypothesis its total energy is unaltered during the flow, it follows that what it gains in kinetic energy it must lose in pressure energy, the sum of these two remaining constant from one end of the pipe to the other.

Or, putting the above argument into mathematical form :—

If $p$ be the pressure intensity in lbs. per sq. ft.
$W$ the weight per cubic foot
and $V$ the velocity then

$$\frac{p}{W}+\frac{V^2}{2g}+Z=\text{Constant.}$$

Where $\frac{p}{W}$ is the pressure energy per lb.

$\frac{V^2}{2g}$ is the kinetic energy per lb.

And $Z$ is the potential energy per lb., $Z$ being a height above some datum to be fixed for any particular case. The equation neglects the effect of viscosity and the magnitude of the effect of this will be seen later.

Taking the case of the Venturi tube shown in Fig. 93.

If $A$ and $a$ be the areas of main pipe and of throat, then assuming the pipe is horizontal

$$\frac{p_A}{W}+\frac{y_A{}^2}{2g}=\frac{pa}{W}+\frac{Va^2}{2g}$$

$$\therefore \quad \frac{p-pa}{W}=\frac{Va^2-V_A{}^2}{2g}$$

For continuity of flow

$$Va=V_A\,\frac{A}{a}$$

$$\therefore \quad \frac{P_A-P_a}{W}=\frac{V_A{}^2}{2g}\left[\left(\frac{A}{a}\right)^2-1\right]$$

Or

$$V_A=\sqrt{\frac{2g(p_A-P_a)}{W[(\frac{A}{a})^2-1]}}$$

Hence the difference of pressure is proportional to the square of the velocity. Owing to viscosity, the actual velocity is less, but in large pipes it reaches 99·5 per cent of the calculated value. Unfortunately the variation from the theoretical value varies with the size, and considerably with the velocity, so a check calibration is necessary.

The experimental laws governing the flow of liquids through expanding ajutages were worked out by an Italian named Venturi, who lived in Paris during the French Revolution. He observed that suction was produced at the throat of the ajutage and proposed to use such suction as a pump to lift water.

A striking illustration of the "Venturi" law can be obtained by repeating the experiment of the late Mr. W. Froude, in which two small glass reservoirs are provided, each being fitted with a horizontal conical delivery pipe. The apertures of these truncated cones are placed in line with one another, but about half an inch apart. The left-hand container is then supplied with water, which, upon being allowed to flow through the conical outlet, jumps across the intervening space, enters the orifice of the right-hand container, and rises in it until the level is within an inch or two of the level of the left-hand container (Fig. 92).

The application of the principle for the purposes of a water meter was made about 1881 by Mr. Clemens Herschel, in Massachusetts, U.S.A., who gave it the name Venturi meter in honour of the Italian investigator. This type of meter has come into very general use for the measurement of large supplies. It is recorded that some of the meters in use measure five hundred million gallons per day, passing through a 210-inch conduit.

The general method of construction is illustrated in the diagram (Fig. 93). The inlet converges sharply to the throat while the outlet expands more gradually; an angle of divergence of $5^\circ\ 6'$ gives the best results in the reconversion of kinetic to pressure energy. In practice a hollow belt is cast around the pipe at the up-stream side, where the

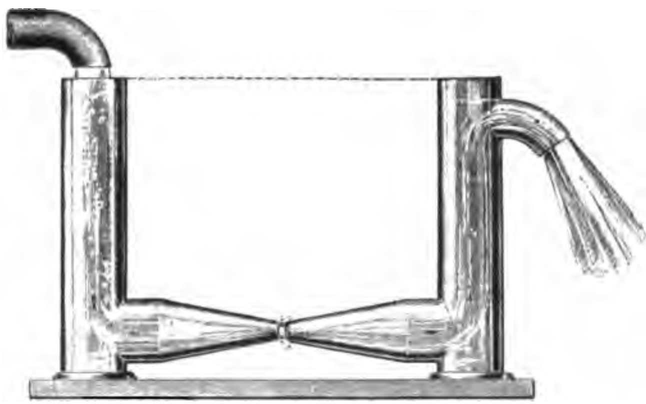


*Fig. 92*

pressure is observed, and the interior of the belt communicates with the interior of the pipe by four small holes. These holes are bushed with vulcanite to prevent incrustation. The throat is lined with a gun-metal casting, having an annular space round its centre which communicates with the interior by four small holes. By careful smoothing of the curves it is possible to recover about six-sevenths of the differential pressure

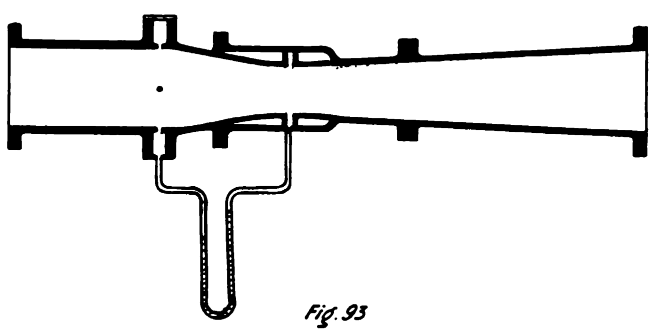


*Fig. 93*

obtained at the throat and also ensure that the square root law is almost exactly obeyed. The actual velocity corresponding to a given fall of pressure is less than the calculated from the formula owing to the surface roughness of the pipe. Herschel found that the formula required a coefficient varying from ·94 to nearly unity, being generally between ·96 and ·99.

The ratio of convergence $\frac{A}{a}$ is generally 9 to 1, but of course is adjusted to meet the requirements of each case. Too high a ratio of convergence is generally inadmissible owing to the loss of head in passing the meter.

*Friction Loss.*—The friction loss depends upon the viscosity of the liquid and the roughness of the pipe, but taking the case of water flowing through a smooth 6″ pipe tests have shown that with a velocity in the main of two feet per second the "Venturi head" would be 5·16 feet and the "friction head" 0·79 feet for the case of a meter having a throat area of one-ninth of the main. At the speed of three feet per second in a main, which is generally regarded as the maximum advisable, the "Venturi head" would be 12·7 feet and the "friction loss" 1·9 feet.

*Recording Meter for Venturi.*—In practice it is desirable to have a record of the quantity passing at any instant. In one form of meter this is effected by means of the following device: At the base of the instrument are arranged a couple of cylinders filled with water. From the bottom of each cylinder a pipe leads off to the Venturi, one being coupled to the up-stream and the other at the throat; hence the height of the water column is the head at the point of the Venturi to which it is coupled. As a consequence, when water is flowing through the meter, the water stands at different levels in the two tubes. In each tube is a float resting on the surface of the water and moving with the latter. A pen connected with one of these floats can trace, therefore, on a suitable clock-

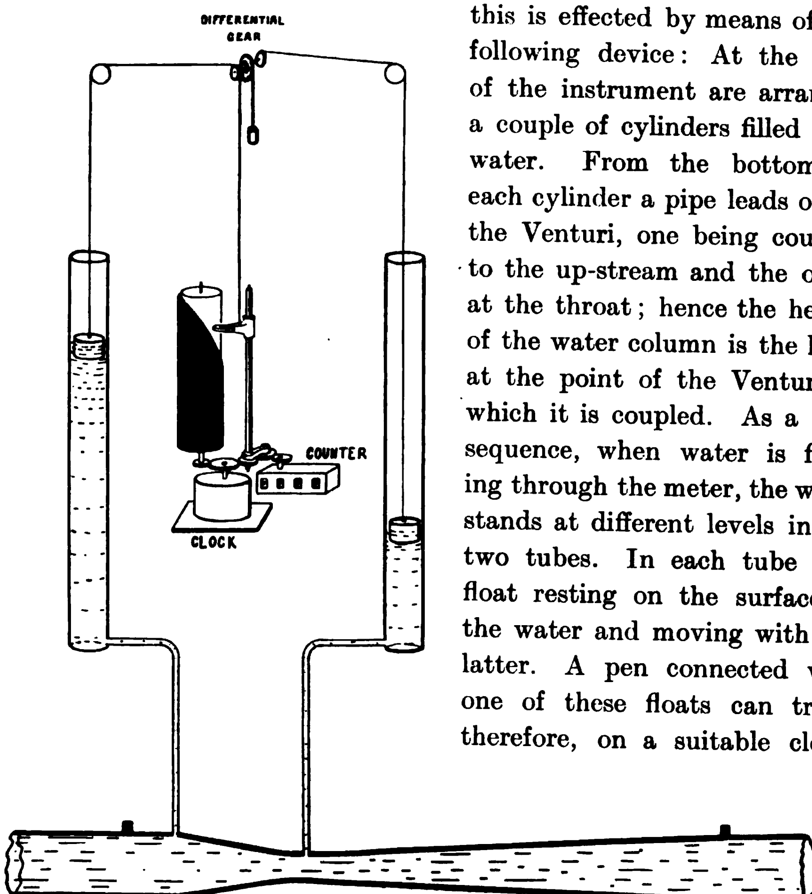



Fig. 94

driven drum, a diagram which shows the rate of flow through the meter at every hour of the day, and from this record it is possible to find the total quantity discharged in any time. The instrument (Fig. 94) is, however, arranged so that it automatically registers on a dial the total quantity passed, so eliminating the trouble of integrating the diagrams. For this purpose a drum is employed, which is driven on a vertical axis by the clock at a fairly rapid rate, say six revolutions per hour. A small wheel mounted on a rod connected to the floats in the water tubes is pressed against this drum by a spring. To the surface of the drum is fastened a sheet of metál cut in the form of a parabola (Fig. 95), so that the surface of the drum is on two levels, and as the parabolic sheet comes round, the small wheel rises up on to it against the tension of its spring. This motion of the wheel in and out from the axis of the drum throws a small pinion in and out of gear with a wheel driven by the clock. If, for example, there is a high velocity through the throat of the Venturi, the float in one tube will have sunk almost to the full extent of its possible travel, and as a consequence the wheel will have been carried nearly to the bottom of the cam drum, at which point the parabolic sheet is very narrow; hence the pinion will be in gear for almost the whole of each revolution. On the other hand, if the rate of flow is small, the surface of the water will rise and the wheel be lifted to a level near the top of the drum, where the parabolic sheet is very wide, and as a consequence the pinion will be held out of gear for most of each revolution. The counter being driven by this pinion records therefore the actual quantity passed, although the difference in level of the water in the tubes varies as the square of this quantity. An equalising pipe connects the two vertical tubes at the bottom, and by opening the cock, when there is no flow through the Venturi, the water level in the two tubes can be adjusted. This equalising pipe is, however, always closed when the water is passing the meter. As a consequence, the water level in one tube is raised, and in the other lowered, and this displacement of the water levels is transferred through a differential gear to the recorder and integrator. This differential gear is necessary since the

Fig. 95 Projection of surface of drum

*The drum is represented on diagram as having been rolled out: the part that is coloured black represents the recessed portion and the other the raised.*

static level of the water varies considerably. It is therefore essential that the recording device shall be operated only by a difference in the level of the two floats, and unaffected by a simultaneous rise or fall of both.

*Advantages and Disadvantages of the Venturi Meter.*—The disadvantages of the Venturi tube are (1) high initial cost and installation; (2) great length; (3) impossibility of altering the range of differential pressures without replacing the meter. On the other hand, it possesses the great advantages that the flow through Venturi tubes of large diameter can be predicted from theoretical consideration with a reasonable degree of certainty, when it would be exceedingly difficult to calibrate them directly owing to large volumes which would be involved.

It might be remarked that this type of meter is also used for the measurement of gas and steam flow, and is further dealt with on pages 109, 131.

### (e) NOTCH METERS

Liquid meters in which the volume discharged is determined by the height of the liquid in a notch differ in principle from those previously described. They are strictly flow meters, giving at any instant the volume flowing per unit time over the notch. When it is desired to ascertain the total volume which has passed in a certain time it is necessary to add a clockwork integrating mechanism. It will be observed that the function of the clockwork in the meter illustrated in Fig. 76 (page 67) was to perform the converse operation, i.e. indicate the rate of flow when the meter proper was an integrator.

Notch meters are of considerable service when the liquid to be metered contain gritty material which would cause serious wear and tear if passed through the piston pumps meters. The best known notch meter is the V form. In 1861 Professor James Thomson (brother of Lord Kelvin) showed that the rate of flow over a V notch was governed by a very simple formula. For a right-angled notch

$$Q=2{\cdot}536 \quad H^{\frac{5}{2}} \text{ cubic feet per second.}$$

This formula was found to hold to better than 1 per cent with the results obtained, with heads varying from two inches to seven inches. The formula presupposes the notch being placed in the side of an infinite reservoir, and it is not strictly valid when the stream has initial velocity. Table IV gives the flow for various depths of stream in the case of a 90° *V* notch.

## TABLE IV

### Flow through 90° V Notches

| Depth in Notch in inches. | Flow per hour. | | Depth in Notch in inches. | Flow per hour. | |
|---|---|---|---|---|---|
| | Gallons. | Pounds. | | Gallons. | Pounds. |
| 1 inch . . | 114 | 1,140 | 9 inches . . | 27,796 | 277,960 |
| 2 inches . . | 648 | 6,480 | 10 ,, . . | 36,174 | 361,740 |
| 3 ,, . . | 1,783 | 17,830 | 11 ,, . . | 45,9 3 | 459,030 |
| 4 ,, . . | 3,661 | 36,610 | 12 ,, . . | 56,872 | 568,720 |
| 5 ,, . . | 6,394 | 63,940 | 13 ,, . . | 69,471 | 694,710 |
| 6 ,, . . | 10,086 | 100,860 | 14 ,, . . | 83,611 | 836,110 |
| 7 ,, . . | 14,829 | 148,290 | 15 ,, . . | 99,351 | 993,510 |
| 8 ,, . . | 20,706 | 207,060 | | | |

The formula for the flow in cases where the angle differs from 90° are not so simple, but this is a point of secondary importance when the meters are empirically calibrated. Fig. 96 is a photograph showing the ideal form of the stream over a V notch. In practice the height of the stream in the notch is shown by means of a float connected to a spindle. The immersion of the float being proportional to the density of the water, compensation for change of temperature is automatic.

Fig. 96

*The Lea Recorder.*—The Lea Recorder has an ingenious arrangement to convert the movement of the spindle which varies as $H_1$ into a movement varying as $H^{\frac{5}{2}}$ for the pen which accordingly has a deflection proportional to the rate of flow over the notch. This is effected as follows: The float spindle is provided with a rack which gears into a small pinion upon the axis of a drum, which drum has a screwed thread upon its periphery. The contour of the thread is the curve of flow for the notch, and just as the flow through a notch increases rapidly with its depth, so the pitch of the screw increases *pro rata* (Fig. 97). Above the spiral drum is a horizontal slider bar, supported upon pivoted rollers and carrying an arm, which is provided with a pen point in contact with a chart upon a clock-driven recording drum. As the float rises, the

movement of the spiral drum is imparted to the pen-arm by the saddle-arm, which engages at its lower end with the screwed thread. It will be noted from the foregoing that the depth of water in the notch can be observed at any time, and that the recording pen, which moves in direct proportion to the flow, produces a diagram whose area is a measure of the total flow ; and as each square inch of area represents so many pounds of water, the addition of a clock turning a cylinder having a scroll cut-in toothed wheel enables an integrating mechanism to

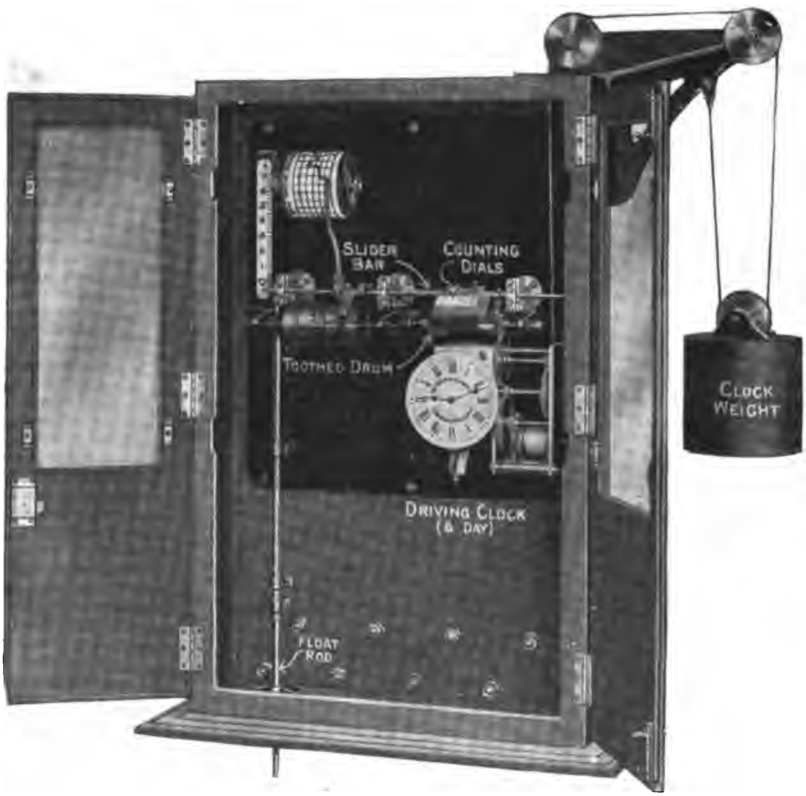



*Fig. 98. COMBINED RECORDER AND INTEGRATOR*

be operated on a step-by-step method (Fig. 98). Readers acquainted with the arithmometer calculating machine will recognise the principle involved.

The toothed drum rotates at a uniform rate, and the small pinion engages for a definite angular interval during each rotation, dependent upon its longitudinal displacement. The counter is thus actuated for a varying time interval which is a function of the height of the water above the notch.

*The Glenfield and Kennedy Meter.*—The Glenfield and Kennedy is another well-known form of notch meter in which a cam is employed to convert a $n^{th}$ power law into a linear function of the quantity. This cam is a profiled plate, as shown in Fig. 99, which illustrates the complete instrument. The float rotates the cam by means of a cord and gears; a small wheel bears on the cam and slides up and down vertical guides, carrying with it a wire which operates the pen recording on a clockwork-

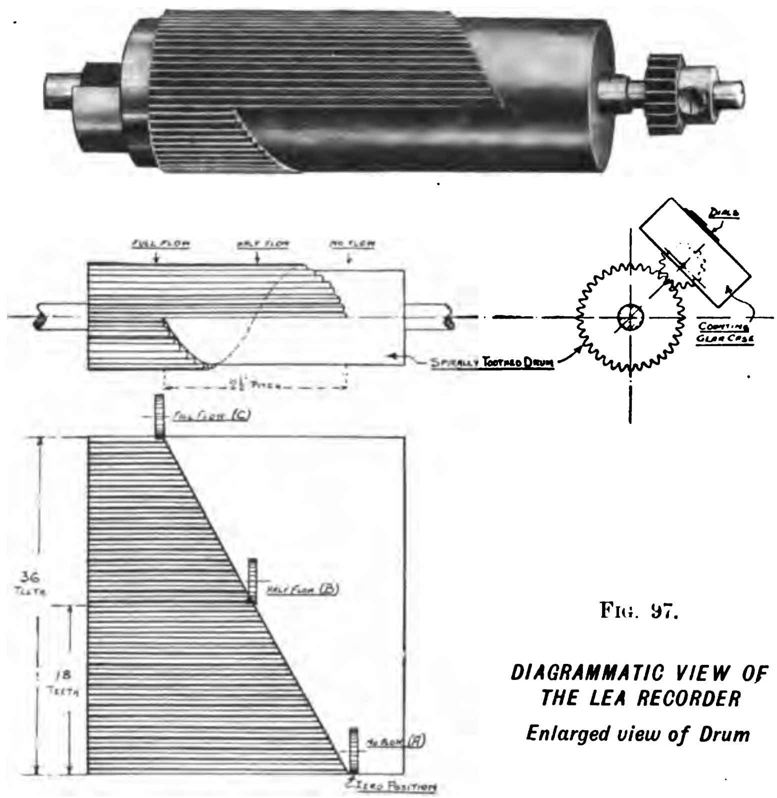



FIG. 97.

*DIAGRAMMATIC VIEW OF THE LEA RECORDER*

*Enlarged view of Drum*

driven drum. No automatic integration device is provided in this meter.

*Yorke Meter.*—In yet another type of meter, known as the Yorke, the weir is so shaped that the rate of flow is strictly proportional to the distance measured between the bottom edge of the weir and the surface of the water. The shape of this notch is such that the submerged area above the sill is proportional to the square root of the head, but as the discharge is also proportional to the same factor, it follows that the height of water in the meter, above the weir sill, is directly proportional to the rate of flow (Fig. 100). A pointer attached to a float moves over

a uniform scale which is graduated to read pounds per hour; the flow is also continuously recorded on a moving chart, and the area of the diagram so formed gives the quantity that has passed during any period in the usual manner. The meter consists of a rectangular tank having the water inlet at one end and the outlet at the other; the weir is a

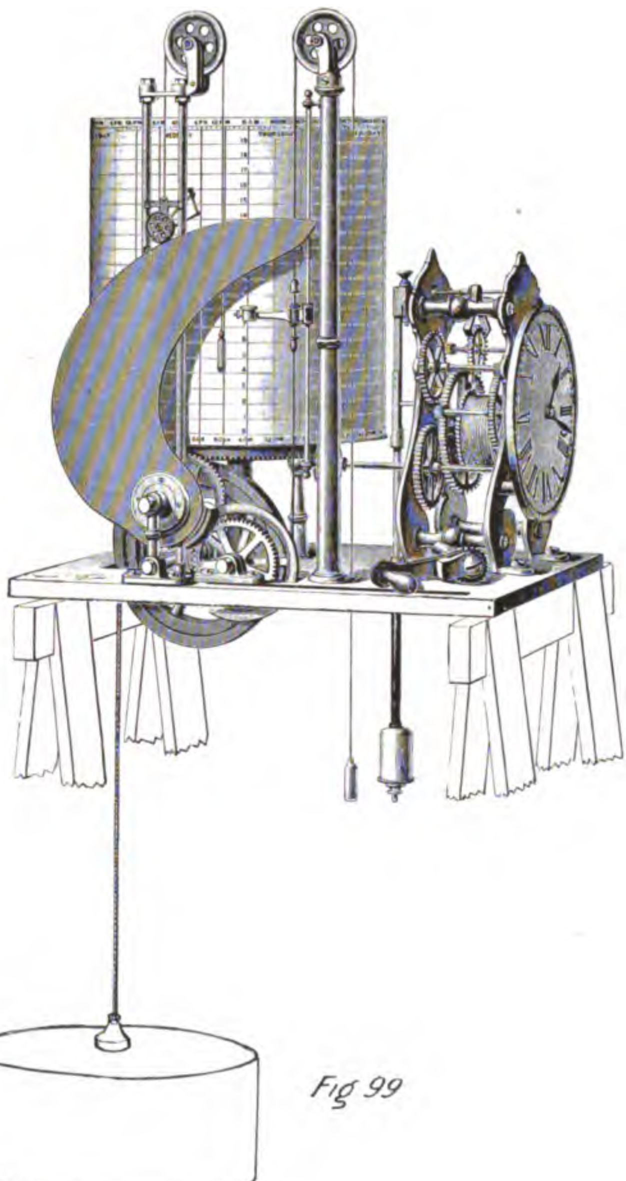


Fig 99

sharp-edged brass plate fixed to a partition near the outlet end, and the float to which the indicator is attached, works inside a vertical cylindrical chamber placed near the inlet, and behind a transverse baffle-plate that reaches nearly to the bottom of the tank. An integrator is employed which is practically an automatic planimeter, as already described in the case of the Kelvin meter (Fig. 101). This consists of an index carrying a trailing wheel, which is moved across the surface of a circular plate rotated by a powerful recorder clock movement. As the flow increases, the index is moved towards the periphery of the revolving disc, and the speed at which the trailing wheel is driven is proportionally greater. The motion of this plate, of course, corresponds to the escapement of the clock, and is therefore in ordinary terms continuous.

Fig. 100

The chief difficulty in the operation of this integrator mechanism is the fact that the zero is somewhat uncertain and the wheel does not always record accurately when near the centre of the disc. One possible method of overcoming this difficulty, which has been used in another connection in America, would be to employ two wheels on the opposite sides of a diameter, and gear both to a differential wheel, so that the rotation of the recording wheel becomes zero at a finite radius.


Fig. 101

*Disadvantages of the Notch type Meter.*—It will be observed that notch meters cannot be operated under pressure, consequently when employed for measuring the feed-water supply to boilers they have to be inserted on the inlet side of the feed pumps. If the pumps leak appreciably, it introduces a source of error in the readings

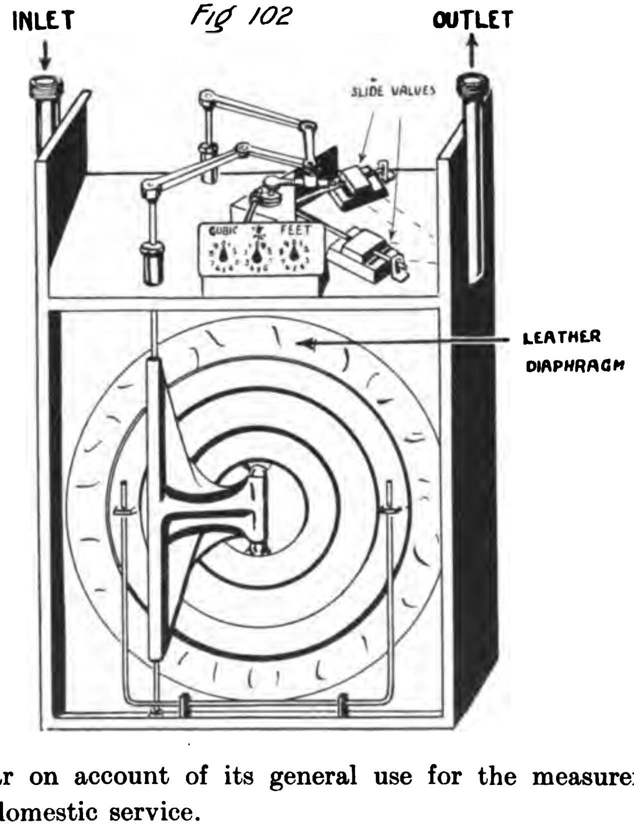
unless allowed for. It is therefore more usual to measure the condensate with this type of meter, which procedure has the advantage that the indication varies more closely with the variations of the load on the plant.

## SECTION II

### (a) METERS FOR THE MEASUREMENTS OF COAL GAS AND AIR

The measurement of gases is effected by meters, which differ very considerably in mechanical detail from those employed in the case of liquids, although these meters may be based on the same fundamental principles. Of the various types, the dry gas meter is probably the

Fig 102




most familiar on account of its general use for the measurement of coal gas in domestic service.

*Dry Gas Meter.*—This meter is of the displacement type and does not require the presence of water for sealing the compartments. Essentially the meter consists of four chambers, which are filled and emptied of gas by the action of the meter mechanism. The number of times

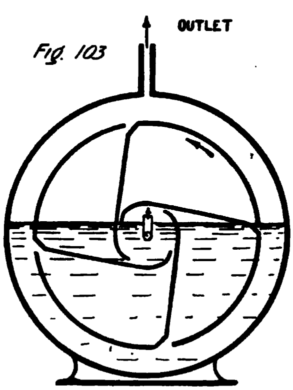
this filling and emptying of the measuring chambers is repeated is indicated on a dial, graduated to read cubic feet.

A sketch of the mechanism of a typical meter is shown in Fig. 102. The casing is subdivided into four compartments by a central partition and two diaphragms. The diaphragms are of special leather fixed to circular steel plates, one of which will be seen in the sketch. Two only of the measuring chambers are shown in the figure. One is the space between the disc with attached leather diaphragm and the middle partition (the plate just behind the diaphragm) of the meter. The other is the space between this same disc and diaphragm and the outside walls of the meter. The other two measuring chambers are like the two described, and are situated symmetrically to them on the opposite side of the middle partition. The filling and emptying of the measuring chambers is effected by the backward and forward movement of the discs, which are restrained by the rods and hinges shown to move parallel to themselves. These discs operate in conjunction with the two slide valves and recording mechanism above the measuring chambers. Each set of two measuring chambers thus constitutes a kind of double-acting bellows, the number of times these are filled and emptied being a measure of the amount of gas passed through the meter.

This type of meter is simple and reliable, and creates very slight back pressure. The accuracy required is not high and the change in mass passed with changes in temperature is usually neglected.

*Wet Meter.*—These are generally built in large sizes for use at gas-works, and consequently are sometimes termed station meters, although small sizes are also made for scientific work, where a greater degree of accuracy is required than can be obtained with the dry type of meter.

Fig. 103




Their construction is essentially that of a drum revolving within a cylindrical tank, which is approximately two-thirds filled with water. The revolving drum consists of a shaft carrying three or four partitions arranged in a spiral form. These partitions emerge in turn from the water as the shaft revolves, and each forms with the water a water-sealed compartment, which alternately receives and delivers gas. The drum receives its motion from the pressure of the gas itself exerted upon its surface. Fig. 103 represents diagrammatically the principle involved

in this type of meter. Actually the meter has the compartments arranged spirally, and the inlet pipe projects into a lenticular chamber at the back of the drum. A gauge-glass with horizontal datum line is also provided, since variations in the water level inside the meter, occurring as they do at the area of maximum cross-section of each chamber, influence to a considerable extent its indications.

Station meters are usually fitted with complex syphon overflows to ensure a constant level. The drum operates the pointer through a stuffing gland and this must be reasonably frictionless, otherwise the pressure drop in the meter is considerable and this affects the capacity. Any stiffness at the gland usually manifests itself by a surging motion of the water in the gauge-glass during the rotation of the drum. For laboratory work the meter should always be started and stopped at the same point, as these meters rarely indicate accurately over fractions of a complete rotation of the drum. The instrument must also be levelled off before use.

### (*b*) The Pitot Tube

The other type of gas meters are based on a measurement of the velocity of the stream and the area of cross-section of the pipe through which it flows. The standard method of measuring the velocity at any point in a stream is by the use of a Pitot tube, an exceedingly simple device named after its originator, Pitot, who described it before the Academy of Science in 1732. A Pitot tube consists of two elements: (1) a dynamic tube pointing up-stream, which determines the dynamic pressure due to the momentum of the stream, and (2) a static tube, which determines the static pressure at the same point in the stream, diagramatically shown in Fig. 104.

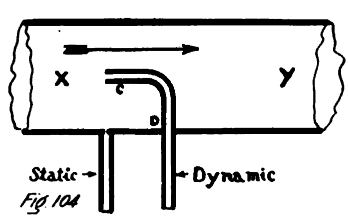


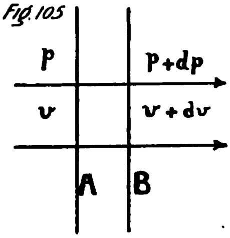
Fig. 104

*Theory of the Pitot Tube.*—Let $X$ $Y$ (Fig. 104) be a portion of a pipe carrying a current of gas in the direction $X$ to $Y$. Let $C$ $D$ be a small tube bent at right angles so that its open end $C$ faces the stream of gas. It is required to find a relation between the velocity and density of the gas stream on the one hand, and the pressure set up by this stream in $C$ $D$ on the other. Consider two parallel planes $A$ and $B$ (Fig. 105) drawn at right angles to the direction of the flow, such that $p$ $v$ are the pressure and velocity over $A$, and $pdp$ and $vdv$ the corresponding pressure and velocity over $B$. Then, dealing with the fluid crossing unit area of these planes,

the gain of momentum per unit time is $\rho v\,dv$, where $\rho$ is the density and the force producing this is $-dp$.

Hence we have the equation $\rho v\,dv+dp=o$

Fig. 105




where integating

$$\tfrac{1}{2}\rho v^2+p=\text{a constant.}$$

Taking, then, this equation from a position in the fluid at which the pressure and velocity are $p_0$ and $v_0$ to one in which they are $p_1$ and $v_1$, we have

$$p_1+\tfrac{1}{2}\rho v_1^2=po+\tfrac{1}{2}\rho v_0^2$$

And if we suppose in the second position corresponding to the mouth of the gauge the velocity $v_1$ is zero, one obtains the result $p_1-po=\tfrac{1}{2}\rho v_0^2$.

A static pressure hole in the wall measures $p_0$, so that the pressure read in the gauge is $\tfrac{1}{2}\rho v_0^2$. The National Physical Laboratory has experimentally investigated the above equation by means of a whirling arm, and found that it held within one-tenth per cent up to fifty miles per hour for air. Moreover, further experiments in air and water have shown that it is probably mathematically correct for velocity up to that of sound in the particular fluid considered. The pressure obtained is independent of the dimensions or shape of the dynamic head. Comparisons have been made between a tube 2 mms. bore by 1 cm. external diameter and a cup 5 cms. in diameter, reducing to 1·3 cms.; both gave exactly the same dynamic pressure. The shape of the static holes is extremely important. It is a necessary condition for the measurement of static pressure that the lines of flow of the fluid be straight and parallel to the solid boundary in which the static pressure hole or holes are drilled.

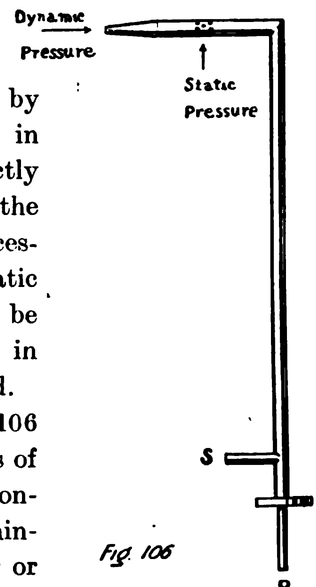



Fig. 106

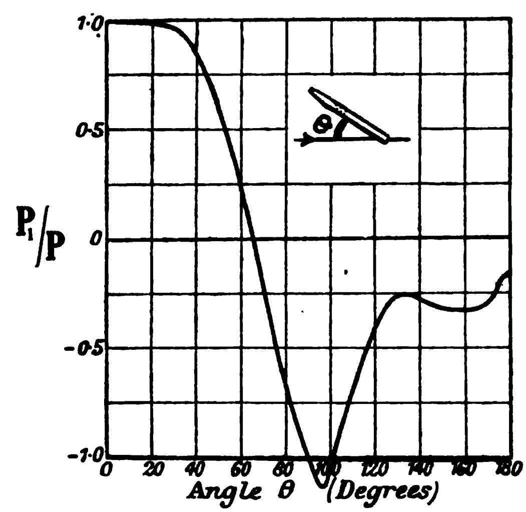
The type of Pitot tube illustrated in Fig. 106 has been developed as the result of a long series of experiments. Two brass tubes are arranged concentrically. The inner or dynamic tube has a thin-lipped orifice facing the air current. The outer or static tube has a conical stopped end, and the small holes are drilled perpendicular to the axis beyond the cone. These holes must be of small diameter and situated far along the parallel portion of the tube. This distance cannot, however, be made

very great, since in practice there is usually a gradient of pressure along the stream being measured. All burrs thrown up must be carefully removed. Any departure from these conditions usually results in an indefinite amount of suction being obtained at the static tube.

The pressure difference is, of course, small, as the table below shows :

| Velocity of air stream. Feet per second. | Pressure in inches of water. | Velocity of air stream. Feet per second. | Pressure in inches of water. |
|---|---|---|---|
| 10 | 0·02 | 60 | 0·82 |
| 20 | 0·09 | 70 | 1·11 |
| 30 | 0·20 | 80 | 1·45 |
| 40 | 0·36 | 90 | 1·84 |
| 50 | 0·57 | 100 | 2·27 |

*Effect of inclining a Pitot Tube.*—It is, of course, assumed that the orifice measuring the dynamic pressure is at right angles to the stream and the static orifices parallel to the stream. The influence of any




EFFECT OF INCLINING A PITOT TUBE

$P$ - Value of $\frac{1}{2}\rho v^2$ when Axis of Pitot is along the Wind

$P_1$ - Value of pressure difference when Axis of Pitot is Inclined at Angle $\theta$ to the Wind.

Fig. 107

error in setting the direction of the Pitot tube may be gauged from the curve shown in Fig. 107, and it will be observed that any small

errors in setting the angle have no appreciable influence. It is probable that the static holes are influenced first by inclinations, but the marked suction due to the open end of the dynamic tube being along the stream will also be observed. The reason that this suction effect does not make itself evident in the case of the static holes, which are, of course, holes perpendicular to the stream of gas, is primarily due to the fact that they are small holes in a continuous surface, and the stream lines are undisturbed by the presence of these holes. The necessity for extreme care, removing burrs, etc., from the edge of the holes, is therefore evident.

Another interesting point about this curve is the effect of having the tube facing down-stream; the static holes are, of course, unaffected, and this negative value of the pressure indicates the increased pressure difference which might be expected by substituting a suction tube facing down-stream for the ordinary static holes of the Pitot tube, as is done in practice for some meters. The slope of the curve is considerable at this point, and therefore this particular pressure head would be much more susceptible to errors in setting in the direction of the stream of gas or the proximity of bends in pipe line into which the pressure head is inserted.

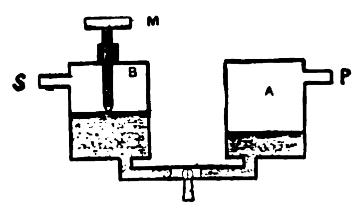
*Measurement of the Pressure Difference.*—Several types of manometer have been devised for the measurement of the small pressure differences obtained from Pitot tubes, and the difficulty of obtaining at the same time a robust and accurate gauge is one of the chief drawbacks of the Pitot tube in practice. For laboratory work, however, several types of differential gauges are available, and the fact that they are only suitable for skilled observers is not a serious disadvantage.

The simplest instrument in use is the micromanometer tube designed by Threfall. The device is shown in Fig. 108 and consists essentially of two air-tight vessels containing water or oil joined together at the base to form a U-tube, and connected respectively to the pressure and static tube of the Pitot head, as indicated in figure. The left-hand vessel is made of glass and is provided with a micrometer, whose point may be adjusted to touch the liquid surface. The two vessels being of the same cross-sectional area, the micrometer reads one-half the pressure difference between the two sides of the U-tube. The micrometer screw is ½ mm. pitch and the head is sub-divided to 0·005 mm. A total pressure difference of 10 cms. can be measured. The graduations are arranged to read actual pressure differences direct.

This method of measuring has the great advantage that its calibration can be predicted from the pitch of the screw, but, on the other hand, it

is somewhat slow in operation and unsuitable for pulsating flow. The smallest pressure difference which can be directly read is one-hundredth of a millimetre head of the liquid employed.

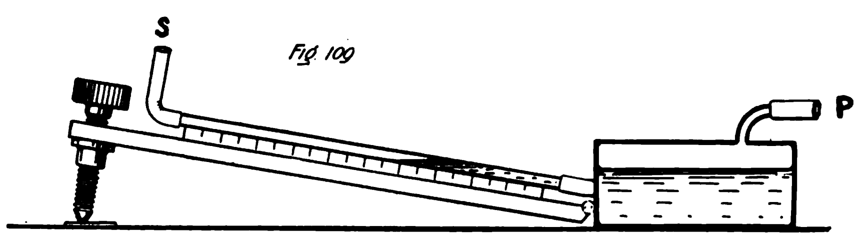
Fig. 108




Diagrammatic Section of Micromanometer.

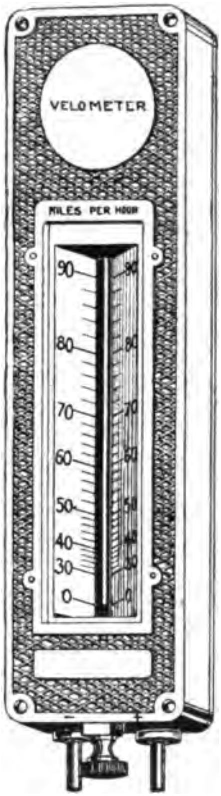
A simple type of gauge for small pressures is the inclined tube manometer. This instrument is a U-tube so arranged that one limb is inclined and the meniscus movement obtained is approximately equal to the change in vertical height divided by the sine of the angle of inclination — the smaller the angle the greater the movement of the column for a given change in height or pressure difference. In practice the minimum inclination is governed by the capillary action of the liquid. The general arrangement of this instrument is shown in Fig. 109. The inclination of the tube can be adjusted to suit any particular requirement. The other limb of the U-tube is made very large in comparison with the cross-section of the inclined tube to reduce the effect of changes in level in this limb. The liquid usually employed is alcohol, with a little colouring matter added. The instrument is convenient and simple, although care must be taken to read the meniscus always with the same direction of motion; either with a falling or rising pressure for accurate work, also the base must be levelled off carefully. The device has found extensive use in conjunction with wind channels in the United States, and has also been used in commercial steam meters in a modified form.

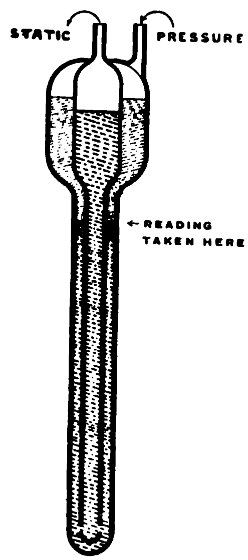
Fig. 109




Another simple and more portable gauge which was at one time

largely used in measuring the speed of aircraft, is the two liquid U-tube. The action of this gauge depends upon the fact that if two links of a large capacity U-tube are joined by a fine bore tube there is considerable motion of any cross-section plane in this fine tube for a small change in level of the U-tube, this being due to the fact that a large quantity of liquid must be transferred through the fine tube for any change in level in the limbs. It remains, therefore, to find some means of rendering a definite plane in the liquid in the connecting tube visible, and this can easily be effected by filling the tube with equal parts of two liquids of slightly different densities, one of the liquids being dyed. Two suitable liquids are a saturated solution of phenol in water and a saturated solution of water in phenol; these two liquids do not mix very readily, and the plane of demarcation is quite a distinct meniscus.




CONCENTRIC GLASS U TUBE

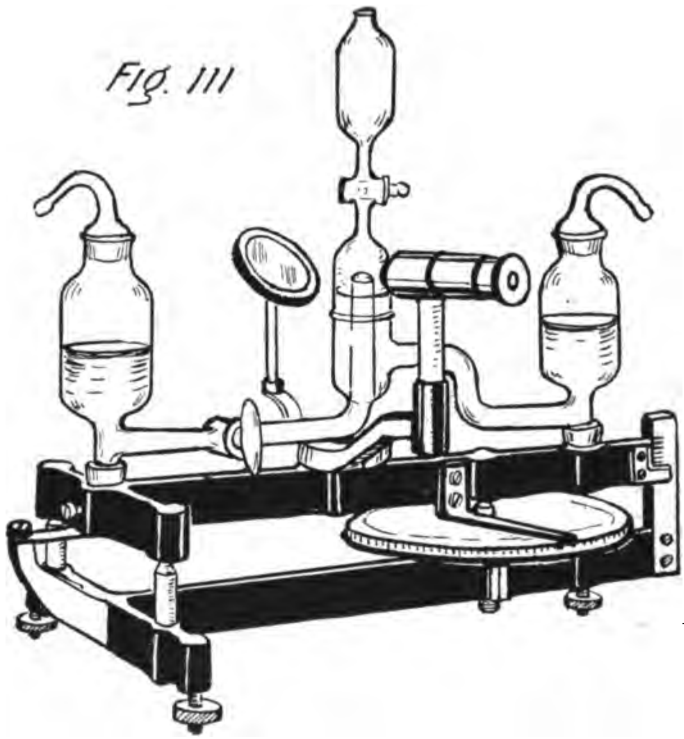
FIG. 110.

The magnification obtained depends on the ratio of the cross-section of the limbs to that of the connecting tube and can be made quite large (about 50 to 1), but the connecting tube must not be too fine in practice; there is also a tendency to leave some liquid clinging to the walls of this tube after rapid changes in level. The form of the gauge used in aircraft is the concentric tube, due to Short (Fig. 110). The principle is identical with the above, but the concentric arrangement eliminates the effect of slight tilting and also equalises the temperature changes in the two limbs. This instrument has now been universally replaced for aircraft by mechanical diaphragm instruments actuating a pointer. These will be referred to later.

The tilting micromanometer is the most generally used form of gauge for accurate work. This form of tilting water gauge was designed

by Professor A. P. Chattock. The principle of the gauge is that of a U-tube in which the difference of pressure on the surfaces of the water in the two limbs of the tube is measured by tilting the gauge through a very small angle, so that there is no displacement of the water along the tube. By this means errors due to capillarity and viscosity are avoided. The glass U-tube is of somewhat unusual form and is mounted on a metal tilting frame as shown in Fig. 111. The left limb of the U-tube

Fig. 111



is continued upwards into, and is concentric with, the central vessel, to which the right limb is connected. This central vessel is filled with oil and water and communicates through a tap at its upper extremity with an oil reservoir for filling. This oil plug indicates any tendency of movement of the water in the connecting tube in a similar manner to the two-liquid gauge already described.

The surface of separation of the oil and the water is formed at the upper extremity of the left limb inside the central vessel. The surface is illuminated by the small mirror shown, and its position observed by means of the microscope attached to the frame. This frame consists of

two parts. The upper part which carries the glass work rests upon three hardened steel points in the lower part. One of these points forms the extremity of the axis of the spindle and wheel by means of which the tilt is measured. The whole frame is supported on three levelling screws. A difference of pressure in the two vessels forming the extremities of the U-tube causes a displacement of the separation surface which is kept in coincidence with the cross-wire of the microscope by rotating the hand wheel. The movement of the gauge is read off on the hand wheel and the pressure head is thus determined.

The dimensions of the gauge are usually such that one revolution of the hand wheel corresponds to a difference of pressure of 0·65 mm. of water, and the graduations on the rim subdivide this into one hundred parts or ·0065 mm. If the pressures are reasonably steady one-fifth or even one-tenth of this fine division can be estimated or a pressure difference of less than 0·001 mm. detected. The maximum pressure difference is 0·8 inches (0·03 lbs. per square inch) and from the above this can be read to 0·000002 lbs. per square inch. For higher pressures a glass portion with greater distances between the vessels, usually twice that of the standard gauge, can be made. The density of the oil used in the central tube has no effect on the calibration and in practice castor oil is the substance which gives the most satisfactory results. This oil, however, has a tendency to intermix, or form some chemical composite while in contact with water, rendering the oil opaque. For this reason a solution of salt (sodium chloride) of 1·07 density is used in the U-tube in preference to pure water, as the gauge then remains clean and serviceable for months and even years. This density correction must, of course, be allowed for in calculating the pressure difference from the dimensions. Care must be observed in practice to avoid sudden changes in pressure which may cause liquid to bubble across through the oil, as the zero of the gauge does not recover for some minutes after this treatment. It is also desirable to use a capillary tube in the circuits if the pressure is unknown, as this damping will allow the adjustment of the gauge to be made before the meniscus is broken. Any damping of this nature should be inserted in both tubes, pressure and static, otherwise the liquid will surge from one vessel to the other with a long period.

A form of gauge which has met with some success in commercial meters and one which depends upon a rather novel principle, is shown diagramatically in Fig. 112. Consider a circular tube which is mounted in stable equilibrum on knife edges and contains a quantity of mercury. The centre of gravity of this mercury will be normally vertically below

the knife edge. If now a small pressure be applied to one side of the tube the mercury will move down in this tube and up in the other side, this movement will move the centre of gravity of the mercury out of the vertical plane containing the knife edge and the whole tube will swing around on the knife edge until the moment of the mass $M$ is sufficient

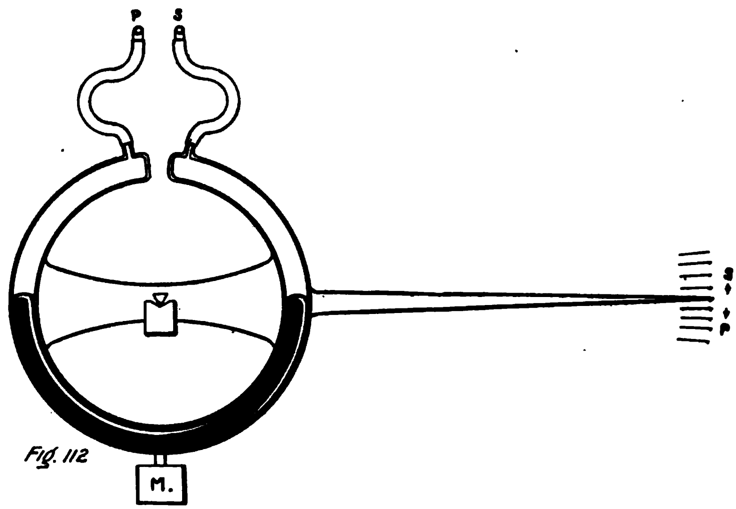



Fig. 112

to counteract the change in the position of the centre of gravity of the mercury. A considerable magnification can thus be obtained, and also a large operating force. The chief difficulty is the limited flexibility of the connecting pipes, and these are in practice placed in line with the knife edge in the form of packing glands.

### (c) Distribution of Velocity over the Section of the Pipe

The Pitot tube gives the velocity at one point in the stream, hence to obtain the total volume passing through the pipe it is necessary to know the distribution of velocity across the section of the pipe. When the motion of the fluid is of stream line form it has been proved mathematically that the velocity distribution is a parabolic curve and that the average velocity over the section is half the velocity at the axis. In the majority of the cases encountered in practice the motion is turbulent, and the distribution of velocity is a function of the roughness of the pipe surface and the viscosity of the fluid. When turbulent motion is present the relation between the maximum velocity (at the axis of the pipe) and the mean velocity over the cross-section varies with the velocity, pipe diameter, and kinematical viscosity of the fluid flowing.

The kinematical viscosity is defined as the ratio of the viscosity to the density of the fluid, i.e. $\eta = \frac{\mu}{\rho}$

Where $\eta$ is the kinematical viscosity
$\mu$ the usual coefficient of viscosity,
and $\rho$ the density of the fluid.

Although it was long realised that there was some connexion between the physical properties of the fluid and the relation between maximum and mean velocities of flow, it was only when the bearing of the general principle of dynamical similarity on the problem was appreciated

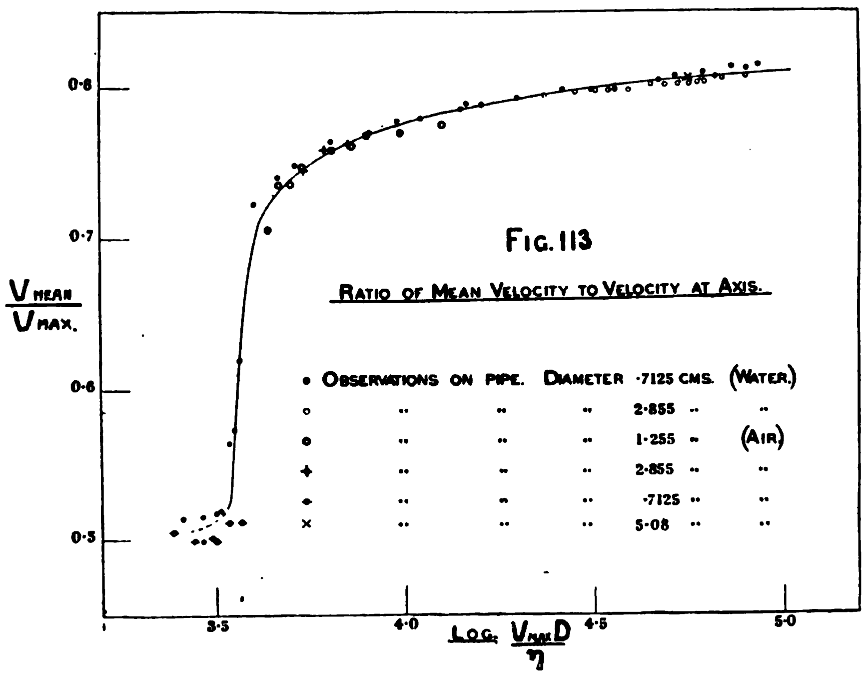



FIG. 113

RATIO OF MEAN VELOCITY TO VELOCITY AT AXIS.

that it became possible to predict the value of the coefficient giving the ratio of the mean velocity to the maximum velocity for any particular case. Theory and experiments have shown that the curve giving the relation between ratio of $\frac{V \text{ mean}}{V \text{ max.}}$ and the quantity $\frac{V D}{\eta}$ is the same for all fluids ; $D$ being the diameter of the pipe.

Stanton and Pannell determined the form of this curve, taking two fluids, air and water, and pipes of various diameters. The form of the curve is shown in Fig. 113, while Table V gives a selection of the experimental date on which the curve is based.

TABLE V.

| Mean velocities. Centimetres per second. | Observed velocity at axis (maximum). | Ratio of mean velocity to maximum velocity. | Nature of flow. |
|---|---|---|---|
| 167·5 | 208·8 | 0·803 | Water in pipe 2·855 cm. diameter |
| 129·9 | 162·0 | 0·802 | |
| 105·7 | 132·4 | 0·789 | |
| 94·5 | 118·6 | 0·798 | |
| 62·8 | 79·0 | 0·795 | |
| 42·4 | 53·7 | 0·789 | |
| 37·0 | 47·1 | 0·786 | |
| 153·4 | 191·4 | 0·802 | |
| 217·2 | 269·4 | 0·807 | |
| 194·6 | 246·7 | 0·789 | Water in pipe 0·7125 cm. diameter |
| 145·9 | 187·0 | 0·780 | |
| 104·4 | 135·5 | 0·770 | |
| 65·20 | 87·07 | 0·748 | |
| 22·25 | 43·28 | 0·514 | Water in pipe 0·7125 cm. diameter |
| 512·9 | 642·4 | 0·799 | |
| 733·0 | 906·8 | 0·808 | |
| 872·0 | 1076 | 0·810 | |
| 1028 | 1264 | 0·813 | |
| 573·9 | 757·2 | 0·758 | Water in pipe 1·255 cm. diameter |
| 115·5 | 149·0 | 0·775 | |
| 648·8 | 853·0 | 0·761 | |
| 471·5 | 631·3 | 0·747 | |
| 893·6 | 116·1 | 0·770 | |
| 240·7 | 317·4 | 0·758 | Water in pipe 2·855 cm. diameter |
| 283·6 | 372·3 | 0·762 | |
| 207·7 | 281·8 | 0·745 | |
| 504·5 | 840·0 | 0·611 | Water in diameter 0·7125 cm. diameter |
| 364·0 | 712·2 | 0·511 | |
| 256·2 | 505·7 | 0·505 | |

The velocity at the axis $V$ (maximum) was determined by means of the Pitot tube, and $V$ (mean) is calculated from the quantity discharged.

Values of the log $V$ max. $\frac{D}{\eta}$ are plotted as obscissae, the logarithm being used for convenience in graphical representation. It will be observed that the value of the ratio varies from 0·5 at the lowest value of the speed, i.e. $\frac{VD}{\eta}=2500$ to 0·81 at the value $\frac{VD}{\eta}=70{,}000$.

Stanton also demonstrated experimentally the identity of the distribution curves for two pipes when the conditions of dynamical similarity were fulfilled. This curve is plotted in Fig. 114. It should be observed that the similarity must extend to the condition of the surface of the pipe, and the results shown in Fig. 114 were obtained with pipes of geometrically similar roughness. In the case of ordinary smooth pipes of commercial solid drawn brass the distribution of velocity was not the same as the curves in Fig. 115 show.

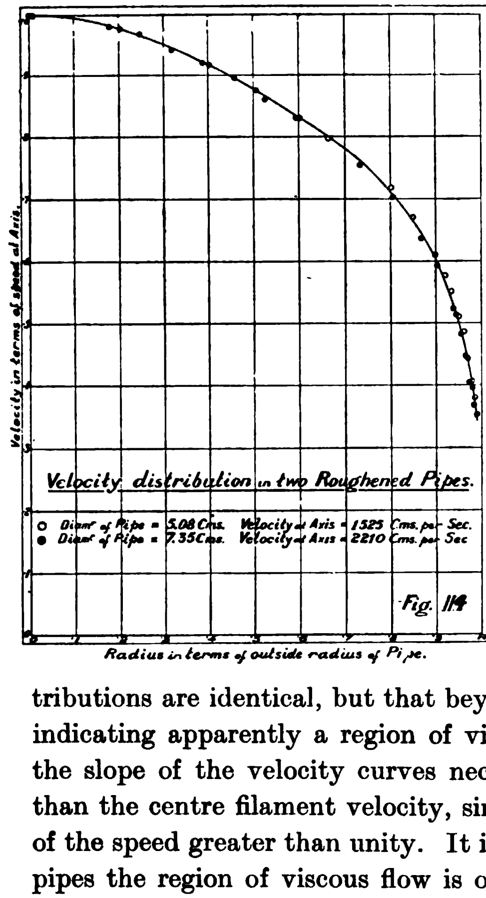


Fig. 114

Under these circumstances the Principle of Dynamical Similarity is not sufficient to enable the mean velocity, and hence the discharge through the pipe to be determined from a single observation of the velocity of flow as the axis. It will be observed that for a region extending from the axis up to a value of the radius of approximately 0·8 $R$, the distributions are identical, but that beyond this radius the curves separate, indicating apparently a region of viscous flow near the walls in which the slope of the velocity curves necessarily increases at a greater rate than the centre filament velocity, since the resistance varies as a power of the speed greater than unity. It is evident that in the case of smooth pipes the region of viscous flow is of considerably greater area than in the case of the roughened pipe, in which it appears to be almost completely destroyed. The experiments proved that the central portions of the velocity distribution curves up to a radius of 0·8 $R$ were parabolic in form. The general form of the $\frac{VD}{\eta}$ curve (Fig. 113) at once indicates the importance of using a fairly high velocity of flow in the pipe when a Pitot tube is employed in small pipes, since the distribution curve varies quite rapidly when $\frac{VD}{\eta}$ is small and the same coefficient of discharge will not apply even to a moderate range of velocity at this stage.

This Principle of Dynamical Similarity is one of fundamental im-

portance in modern research. By its aid it is possible to predict the performance of full-sized aircraft from small scale experiments on models. The discovery of the Principle in its widest application to all fluids and conditions of flow is the culmination of the researches of large number of scientific workers. The existence of such relationship for some aspects of the problem were predicted by Stokes as early as 1850; later Helmholtz, Osborne Reynolds, Lord Rayleigh, have all contributed to the establishment of the generalisation in its final form.

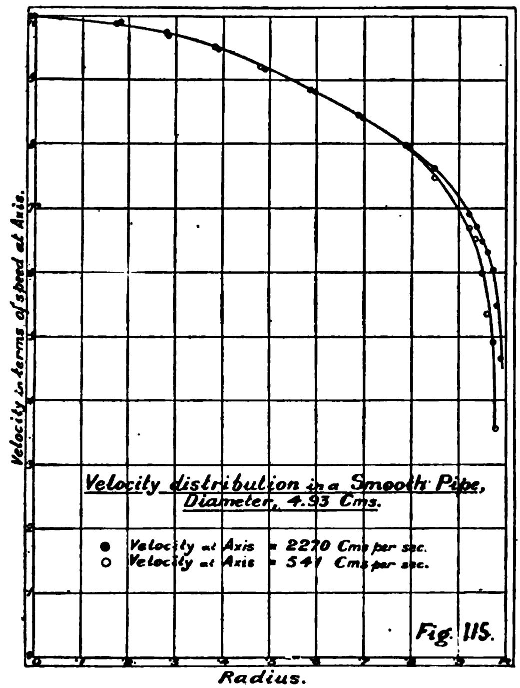


Fig. 115.

The work of Osborne Reynolds is particularly of interest, since it refers to the conditions of fluid flow in pipes. He studied the nature of the flow of water in pipes, and showed by introducing colouring matter into the water flowing through glass tubes that the motion was stream line or lamellar in character at low values of the velocity of flow; and eddying or sinuous at high velocities. The charge from lamellar motion to eddying motion took place suddenly at a definite value of the velocity; this value of the velocity was inversely proportional to the diameter of the tube and directly proportional to the kinematical viscosity.

The experimental work of Stanton fully established the pioneer investigations of Reynolds, but the significance of the Principle of Dynamical Similarity in its application to fluid flow is not yet fully realised by engineers. Further reference to it will be found in the section dealing with the calibration of air and steam meters.

## (d) The Venturi Air Meter

Theoretically the Venturi tube meter is one of the most satisfactory forms of flow meters. The smooth curves of the up-stream and throat-sections ensure that the square root law is almost exactly obeyed, and

the loss of head due to the insertion of the meter in the pipe line is exceedingly small. When used for gases the pressure difference for the majority of practical cases does not exceed one pound per square inch. Consequently it is desirable to have a precision manometer to measure these pressures. Mr. J. L. Hodgson, of Messrs. G. Kent & Co., has developed one convenient form of the U-tube, as shown in Fig. 116.

In this instrument practically the whole change of level takes place in one limb, so that it is only necessary to read the change of level in this limb and make a correction which depends upon the ratio of its cross-sectional area to that of the reservoir into which the up-stream pressure is introduced. The diameter of this reservoir is large, so that any slight variation in the internal diameter of the gauge-glasses fitted involves no appreciable change in the constant by which the readings of the instrument have to be multiplied. The change of level of the liquid in the gauge-glass is measured by means of a travelling microscope which is moved by a guide-screw having ten threads per inch. A graduated dial is fitted in connection with the handle by which this screw is rotated, so that readings accurate to less than one thousandth part of an inch can be taken.

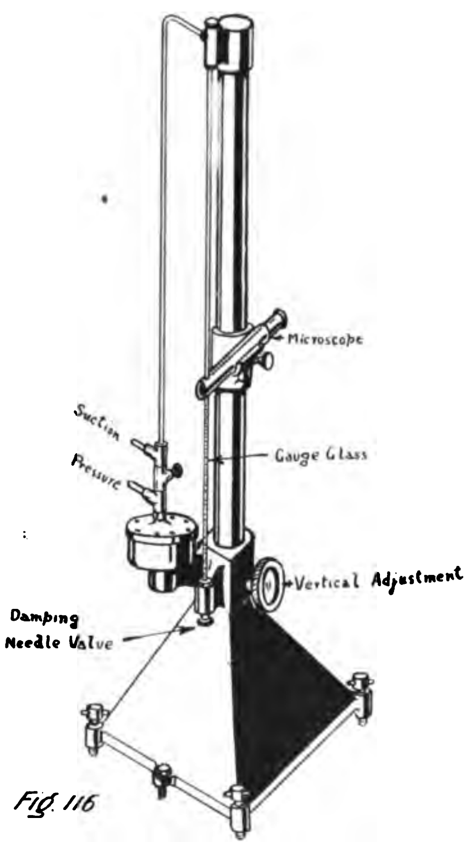


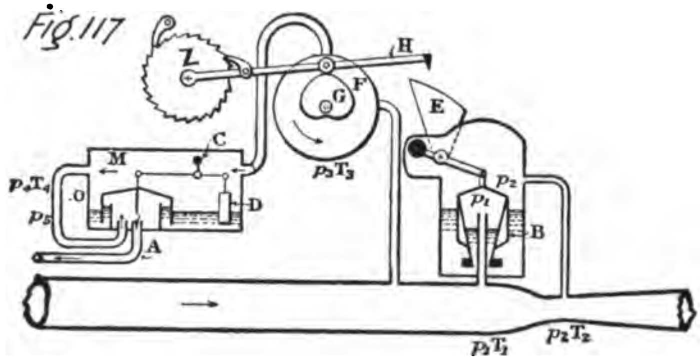
Fig. 116

One of the difficulties met with in designing an instrument that would enable a change of liquid level to be read to anything like this degree of accuracy was the difficulty of obtaining a definite and consistent reading on the meniscus. It was overcome by using a microscope of about thirty diameters magnifying power and a gauge-glass of five-sixteenths part of an inch internal diameter, and illuminating the meniscus always in the same direction. It will be seen (Fig. 116) that the gauge-glass passes through a tube which slides on the end of the microscope. The inside of this tube is blackened to prevent

cross-reflection. High accuracy can be obtained only by using oil or alcohol as the manometer liquid, since, even with the cleanest possible gauge-glass, a water meniscus is apt to be sluggish. The accuracy of the guide-screw, by means of which the microscope is traversed, need not be of very high order, as great precision in the measurement is only essential at the low heads.

*Venturi Meter Compensated for Variations in the Specific Gravity of the Gas.*—When the density or pressure of the gas whose volume is to be measured is not constant, it becomes necessary to arrange that this variation be automatically compensated for. For example, in the metering of coal gas the density of the gas varies with the quality of the coal and the conditions of manufacture. A recording Venturi gas meter was designed by Hodgson for gas works use to register the actual volume

Fig. 117




passing independently of variations in specific gravity of the gas. It is shown diagrammatically in Fig. 117.

The Venturi head is measured by a water-sealed bell whose motion is transmitted by suitable means to a cam $E$. This is so shaped that the feeler $H$ which comes into contact with it adds on to the counter-reading an amount proportional to the square root of the Venturi head at each revolution of the heart-shaped cam $G$ which actuates it. If this heart-shaped cam were rotated at a uniform speed by $F$ the rate of registration for a given flow in the main would be proportional to the square root of the density of the gas passing, and the meter would therefore only read correctly for gas of a particular density. The correction for variations in the density of the gas is obtained by making the speed of rotation of the heart-shaped cam depend upon the density by driving it by means of a small wet gas meter $F$, which is rotated continuously by gas escaping from the main through a small orifice $A$ to the atmosphere,

the pressure across this orifice being maintained constant by a specially sensitive regulating-valve. Since the rate of flow through this orifice, across which the difference of pressure is maintained constant, is inversely proportional to the square root of the density of the gas, the variation in speed of the wet meter gives the exact compensation required, and the counter registers the actual volume passing. It will be observed from Fig. 117 that the regulating-valve is compensated for changes of level of the liquid seal by means of the displacer $D$, and for variations in the inclination of the balance-arm by the weight $C$. The ratio of the area of the bell to the area of the controlled orifice is made large enough to prevent variations in the pressure from affecting the accuracy of working. In practice the valve maintains the head across the orifice $O$ correct to within $\pm 0{\cdot}002$ inch of water.

*Mathematical Theory of this Gas Meter.*—The gaseous discharge in cubic feet per minute through a Venturi tube is given by the relation

$$D_1 = K_1\left[\frac{(p_1 - p_2)\,T_1}{\triangle\, p_2}\right]^{\frac{1}{2}} \text{——(1)}$$

Where $T_1$ is the absolute temperature and $p_1$ the absolute pressure at the Venturi up-stream, $p_2$ the absolute pressure at the Venturi throat, $K$ a numerical constant, and $\triangle$ the specific gravity of the gas relative to air. The distance between the zero position of the point of the feeler $H$ and the surface of the cam $E$ is made proportional to $(p_1 - p_2)^{\frac{1}{2}}$ for each position which the cam is caused to take up by the bell $B$. Each time the feeler is raised from the surface of the cam, an amount proportional to this distance is added on to the counter-train $Z$ by means of a pawl and ratchet. The counter thus registers an amount proportional to

$$[p_1 - p_2]^{\frac{1}{2}} \times M \text{——(2)}$$

Where $M$ is the number of revolutions per minute of the meter $F$.

The rate of rotation of this meter depends upon the discharge through the orifice $O$, which is given by the relation

$$D_4 = K_4\left[\frac{(p_4 - p_5\,T_4}{\triangle\, p_5}\right] \text{——(3)}$$

Where $p_4$ and $p_5$ are the pressures on the up-stream and down-stream sides of the orifice respectively and $T_4$ the up-stream temperature.

If $D_3$ is the number of cubic feet per minute passing through the meter $F$ at temperature $T_3$ and pressure $p_3$,

$$\begin{aligned} D_3 &= D_4\frac{T_3}{T_4}\cdot\frac{p_4}{p_3} \\ &= K_4\left[\frac{(p_4 - p_5)}{\triangle\cdot\, p_5}\cdot\ T_4\right]^{\frac{1}{2}}\cdot\ \frac{T_3}{T_4}\cdot\frac{p_4}{p_3} \text{——(4)} \end{aligned}$$

Putting $M = K_3\ D_3$

Quantity registered $= K[p_1 - p_2]^{\frac{1}{2}} \times K_3 D_3$

$$= K.K_3.K_4[p_1 - p_2]^{\frac{1}{2}} \left[\frac{(p_4 - p_5).\ T_4}{\triangle \cdot p_5}\right] \cdot \frac{T_3 \cdot}{T_4} \frac{p_4}{p_5} \text{——(5)}$$

Now if $(p_4 - p_5)$ is kept constant by means of the regulating valve $M$, and if, by suitably arranging the apparatus, the temperatures $T_3$ and $T_4$ are made sensibly equal to $T_1$ and the pressures $p_3$, $p_4$ and $p_5$ to $p_2$ equation (5) becomes

$$\text{Quantity registered } K_1 = \left[\frac{(p_1 - p_2\, T_1}{\triangle \cdot\ p_2}\right]^{\frac{1}{2}} \text{——(6)}$$

which is identical with equation (1).

A meter of the above type was tested against a drum type station meter for a period of two years and the indications of the two meters always agreed within + 1 per cent.

The disadvantage of the meter is the liability of the Venturi tube to become clogged with naphthalene, tar, etc. In order to reduce such to a minimum, the tube should be installed vertically in a by-pass with the gas entering from above so that any liquid carried by the gas will drop right through the tube. The throat and the up-stream sections are generally steam heated, a precaution which practically eliminates deposit; also it is sometimes arranged that the throat may be cleansed with water jets without opening up the main.

*Large Venturi Meters for Air Supply Lines with Pressure and Temperature Compensation.*—In the Rand mines power is distributed in the form of compressed air to the mines from large central stations fitted with turbo compressors. The power is charged for on the basis of the electrical energy required to compress each pound of air to the pressure and temperature of delivery. For the metering of the compressed air, supply meters based on the same principle as described above were devised by Hodgson, but of different mechanical construction. The compensation for pressure variation is automatic, but that for temperature is done by hand periodically, the temperature being less liable to sudden alterations. Since the number of air units delivered in any interval of time is a function of the product of the differential pressure in the Venturi, and the actual pressure and temperature of the air, some multiplying device has to be employed to take account of these quantities. Hodgson employs logarithmic cams operating on to a differential gear, each cam being so geared that its angular displacement is proportional to the quantity it represents.

These movements are then added together on a differential gear

(Fig. 118), which communicates to the central spindle, on which it is carried, the algebraic sum of the motions transmitted to it. The motion of this spindle is therefore proportional to the logarithm of the product of these functions, and, by means of an anti-logarithmic cam and feeler, it is transformed into one proportional to the product itself. In this way an angular displacement proportional to the rate of flow in air units per hour is obtained. Amounts proportional to this angular displacement are added to the counter-reading at equal intervals of time by means of a clutch, one member of which is rotated continuously at a uniform rate by a small air-turbine controlled by a centrifugal escapement.

Fig. 118

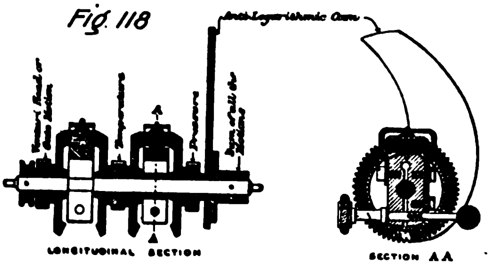
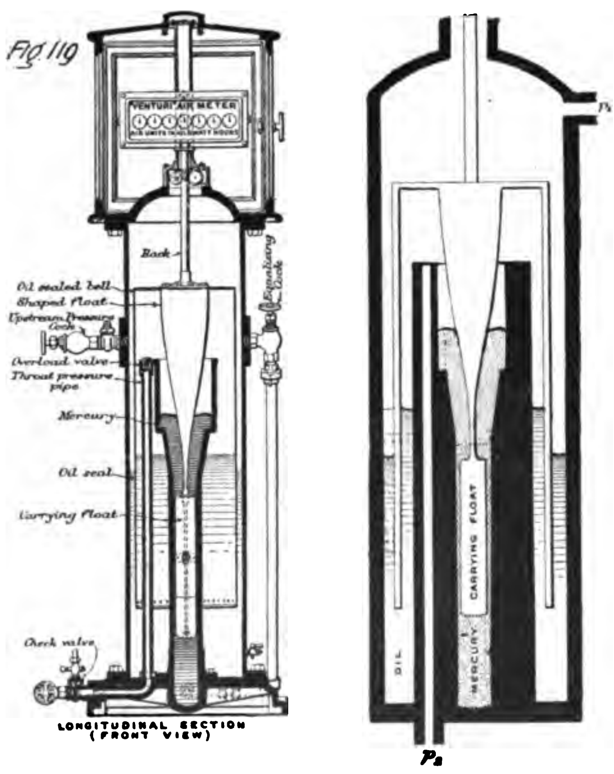



Fig. 119 is a section through the Venturi recorder, which shows the arrangement whereby the differential pressure obtained from the Venturi tube is measured. It consists of a light inverted bell immersed in an oil seal, the throat pressure acting on the inside of the bell, and the up-stream pressure on the outside. An increase of the flow thus causes the bell to descend. The weight of the bell is taken by a carrying float which is always totally immersed in mercury. The displacement of the bell is made proportional to the logarithm of the volume passed by means of a shaped float, the bell descending until the increase in



the difference in pressure is balanced by the increase in buoyancy. The carrying float is built up of slate and vulcanite in the ratio of 1 to 2·46, in order to compensate for changes of temperature, and so prevent error in the zero flotation-level. The arrangement is sensitive to a Venturi head of less than $\frac{1}{10{,}000}$ lb. per square inch and will measure Venturi heads up to 0·85 lbs. per square inch, an accurate range of flow measurement down to one-twentieth of the maximum flow being obtained. A valve is provided whereby the pressure on both sides of the ball may be equalized and its zero checked. The pressure of delivery is measured by a battery of steel diaphragms, which are shown in Fig. 120. The required angular motion is obtained by means of a cam, whose profile is determined by calculation.

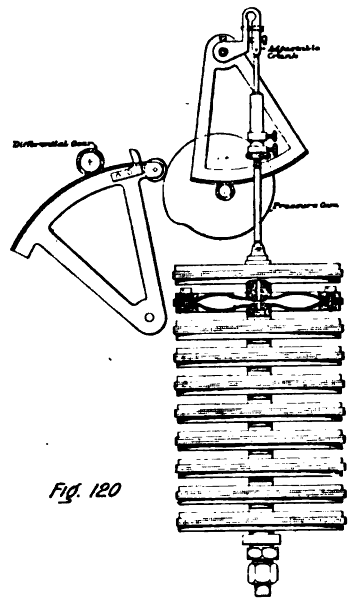


Fig. 120

The diaphragms used are made of untempered steel and are arranged so as to give a small movement of considerable power.

### (e) The Diaphragm Method

A simple device for measuring the flow of gases in pipes which is coming into extended use is a diaphragm inserted in the pipe line with appropriate means of measuring the drop of pressure across it. The

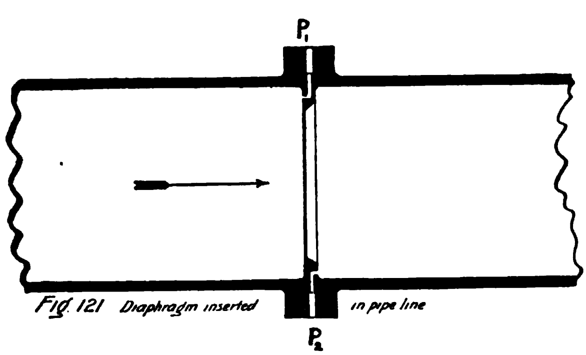



Fig. 121 Diaphragm inserted in pipe line

method, in general principle, is similar to the Venturi tube, but has the advantages both of cheapness and of not requiring considerable alterations in the pipe line. The construction generally takes the form of a thin plate (*placed symmetrically in the pipe line*) (Fig. 121), in which

a square-edged hole is bored. The differential pressure is obtained at the two holes drilled as shown in the diagram. This pressure is measured by the usual types of manometers such as those described above for use with Venturi tubes. A great advantage of the diaphragm method over the Venturi tube lies in the fact that a diaphragm can be easily changed for another, which gives the most suitable pressure drop for the particular recorder available. It is essential that the edges should be square, since it has been found that round-edged orifices give inconsistent results.

The diaphragm orifice must be regarded in the light of a submerged weir notch and as such it sets up a converging stream which reaches

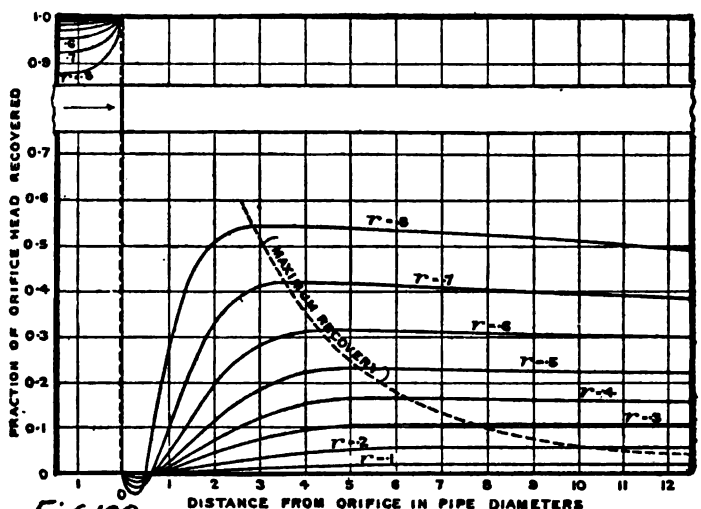


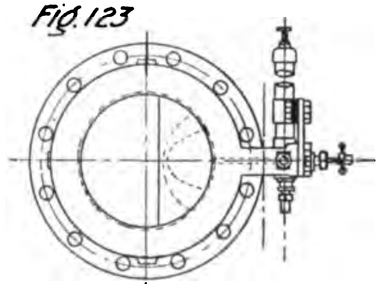

Fig. 122

its maximum contraction some distance down-stream of the orifice. The greatest pressure drop will therefore be at this point of greatest contraction, and Fig. 122 shows the form of this variation curve. Hodgson insists upon the necessity of placing the pressure holes as close to the plate as possible on both sides. Davis and Jordan claim, however, that the best position for the pressure holes is at the section at which normal flow is discontinued and the stream begins to converge as it approaches the orifice on the up-stream side and the section of greatest contraction of the jet after it leaves the orifice on the down-stream side. The positions are stated to be eight-tenths the diameter of the pipe up-stream and four-tenths the diameter of the pipe down-stream for all sizes of pipe. This position is said to give the steadiest reading of the pressure difference and of course gives the highest value ; but

the advantage incurred hardly appears to justify the care necessary in the installation of the pressure holes. The effect of rounding or bevelling the edge of the orifice is at once evident when the idea of a contracted jet is considered, as the area of the stream at its maximum contraction must vary and discharge coefficients obtained by the use of sharp-edged orifices cannot apply. The actual pressure drop is greater than the head lost by the insertion of the diaphragm, and Fig. 122 shows the pressure recovery of the stream. The values here shown are plotted for one particular velocity and various values of $d_2/d_1$, where $d_2$ is the diameter of the pipe. The recovery is greatest for large values of $d_2/d_1$, and point of maximum recovery of pressure travels farther down-stream as the ratio $d_2/d_1$ is reduced. It is worthy of note that in cases where $d_2/d_1$ is large, more than half the differential pressure is recovered without any special means being taken, such as the fitting of a diverging cone, to effect such recovery. In the figure the ratio of $d_2/d_1$ is denoted by $r$.

The laws of flow through orifices have been investigated experimentally by a number of observers. Mr. J. L. Hodgson, in particular, has devoted much time to the development of commercial meters based on this device. In the course of extensive experiment he found that when the diameter of the orifice was more than about three-quarters that of the main, the coefficient of discharge became very dependent upon accurate centring and the smoothness of the pipe surface on the up-stream side of the orifice. This difficulty could be partially overcome by fitting two or more sets of pressure holes. In a further development of this type of meter Hodgson replaced the concentric disc constriction by a plate projecting into the pipe, the whole area of the obstruction being concentrated around the pressure holes in the form of a segment of a circle bounded by a chord. In places where high velocities of flow had to be measured it was found more satisfactory to replace the straight chord by the arc of a circle of which the centre was at the pressure holes, as shown in Fig. 123.

Fig. 123



The law of flow past a constriction may be expressed by the formula :

$$Q = \delta\phi A\,[(P_1 - P_2)W_1]^{\frac{1}{2}} \text{——} (1)$$

Where $Q$ is the discharge in pounds per second, $\delta$ is defined as the "discharge intensity coefficient" for the particular type of constriction. This coefficient includes the discharge coefficient $\Omega$ ; and the ratios

of the area of the main to the area left by the constriction $n$; the actual value of $\delta$ is $\Omega/\sqrt{n^2-1}$——(2)

$\phi$ is a term which allows for the compressibility of the fluid. Its value for various values of $n$ and $P_2/P_1$ is shown graphically in Fig. 124.

$A$ is the area of the pipe at the up-stream pressure hole in square feet.

$P_1$ and $P_2$ are the pressures at the up-stream and down-stream pressure holes respectively in pounds per square inch.

$W_1$ is the density of the fluid in pounds per cubic foot at the up-stream pressure hole.

For pure dry air $W_1=2{\cdot}6998\ P_1/T_1$

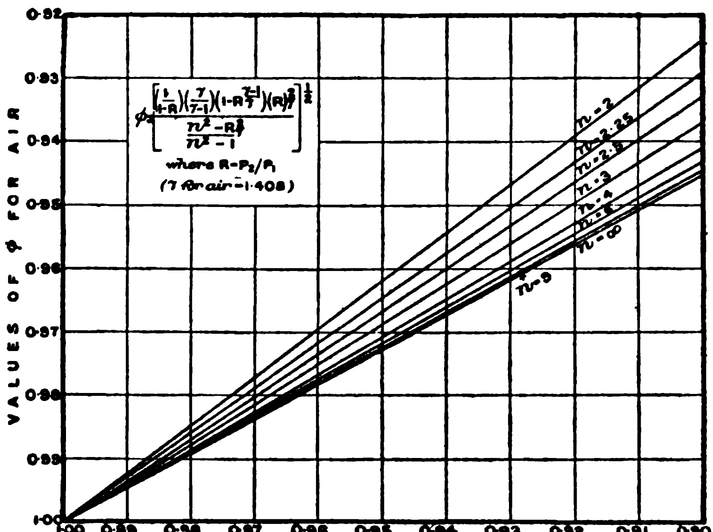



FIG. 124

Where $T_1$ is the absolute temperature in degrees Fahrenheit.

For a square-edged orifice having a diameter less than three-quarters of that of the main, and pressure holes in the plane of the orifice, and for $\phi=1$ (nearly) the equation for the flow reduces to

$$Q=0{\cdot}668\frac{A}{\sqrt{n^2-1}}\left[(P_1-P_2)\frac{P_1}{T_1}\right]^{\frac{1}{2}} \text{ lbs. per second——(3)}$$

*Variation of the Discharge Coefficient, $\Omega$, with the diameter of the Orifice and the Head producing Discharge.*—Hodgson investigated the laws of discharge for a range of diameters varying from one-sixteenth of an inch to nine inches. In these experiments water was used on account of the ease with which it could be metered. As will be shown later in the section on the calibration of air and steam meters, the value

of the discharge coefficient is the same for air and water under certain conditions.

In his experiments, the orifices were in all cases geometrically similar with the pressure holes in the plane of the orifice as shown in Fig. 121. Great care was taken in the preparation of these smaller orifices. They were made in hardened steel to ensure that their edges were exactly square and without the least trace of "wire edge." Their diameters were measured in four directions at 45° to one another by means of a travelling microscope, and these instruments were checked to the nearest ten-thousandth of an inch by means of specially made plug gauges. The orifices were fitted in a length of bored pipe. His results show that, for all values of $d_2$ within these limits, and for all values of $d_2/d_1$ less than 0·7, after the critical head has been reached the coefficient of discharge for any orifice will not differ by more than $\pm 1$ per cent from the value 0·608. Below the critical head the water discharge varies as $(P_1-P_2)^m$, where $m$ is about 0·488.

The experimental values of the discharge coefficient, and approximate[1] values for the critical head, are given for the smaller orifices in the following table :—

| Diameter of up-stream, $d_1$ | Diameter of orifice, $d_2$ | $s/d_2$ (approximate) | $\Omega$ | Critical head of inches of water |
|---|---|---|---|---|
| | Inch | | | |
| 1·5 | 0·0660 | 0·04 | 0·612 | 340 |
| 1·5 | 0·1256 | 0·02 | 0·605 | 250 |
| 1·5 | 0·2412 | 0·02 | 0·607 | 154 |
| 1·5 | 0·3539 | 0·02 | 0·606 | 87 |

S = Thickness of orifice plate in inches.

Hence for values of $d_2/d_1$ which lie between zero and 0·7 the coefficient of discharge does not differ materially from 0·608. These tests on very small orifices are of importance, as they help to show that similar orifices similarly installed may be expected to have the same coefficient of discharge, whatever the diameter.

For values of $d_2/d_1$ which are greater than this, the discharge coefficient gradually diminishes and is so sensitive to minute variations in the conditions under which the orifice is installed, owing to the rapid variations in the pressure immediately up-stream and down-stream of the orifice, that it is preferable to calibrate each individual orifice *in situ.*

[1] The critical head does not occur at any very well-marked point.

It is important that the pressure holes should be in the plane of the orifice, especially when $d_2/d_1$ is large.

In some other experiments in which the flow of air was studied it was found that the discharge coefficients for these square-edged orifices are identical with the water values only in the limit when $P_2/P_1$ is unity. As $P_2/P_1$ diminishes, the discharge coefficient increases according to

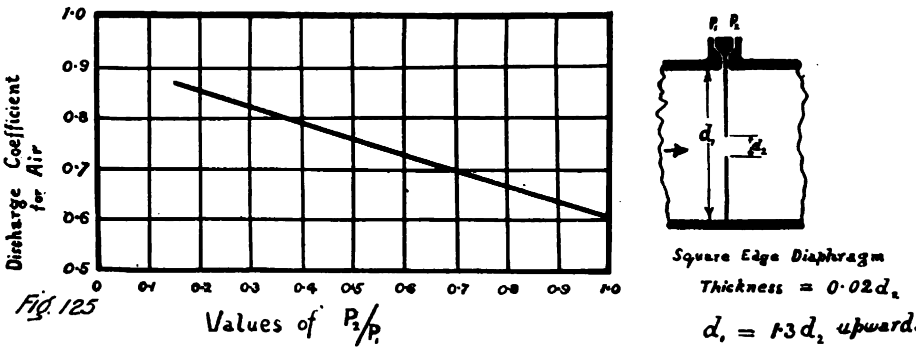


Fig. 125

what is apparently a straight line law, which, if assumed to hold beyond the limits of the experiment which Hodgson was able to make would seem to indicate a value of 0·914 when the ratios $P_2/P_1$ is zero. The values of the discharge coefficient for various values of $P_2/P_1$ is given with fair accuracy by the relation $\Omega = 0{\cdot}914 - 0{\cdot}306\ P_2/P_1$, as shown graphically in Fig. 125, which represents experimental results for the following series of values of $d_2$ :—

| $d_1$ | $d_2$ |
|---|---|
| 5·995″ | 0·670″ |
| ,, | 1·001 |
| ,, | 1·568 |

The same relation holds approximately (within $\pm 1$ per cent) for steam flows. The investigation of the value of the discharge coefficient for square-edged orifices is interesting from a laboratory point of view only, as the sharpness of the square-edge is very apt to be damaged by handling or by erosion due to the flow. The value of the discharge coefficient then increases, and the discharge through the orifice can no longer be inferred with certainty from previous tests. For this reason, Hodgson, although recommending the use of square-edged orifices for standard work on account of the ease with which they may be repro-

duced accurately, and the exactness with which the coefficient is known, uses in commercial work orifices which have slightly rounded edges. The value of the discharge coefficient for such orifices, though it must be determined in each case by actual calibration, changes far less with erosion.

## SECTION III

### (a) Steam Meters

It is only within comparatively recent years that the question of measuring the steam output of a boiler has received the consideration of engineers. This is the more surprising when one reflects that the generator side of the modern power plant is equipped with every type of electrical instrument needful for the efficient distribution of power. The maximum thermal efficiency of a boiler is only obtained for a particular rating, and it is obvious that this can only be found with certainty when the boiler attendant has some means of knowing what the plant is doing. The entire equipment of the past has generally been limited to a pressure gauge and water column, but the tendency at the present day is to make the control and operation of the boiler plant more exact by providing for each unit a thermometer, draught gauge, $CO_2$ recorder, automatic coal weigher and steam flow meter.

At the present time the steam flow meter finds its greatest field of usefulness on individual boiler units. Various designs of the instrument have been tried, most of which have failed from one cause or another, so here it will suffice to describe three types which have met with a certain measure of success under normal working conditions. It must, however, be admitted that the design of a robust meter for the practical measurement of steam flow is an exceedingly difficult problem, owing to the various factors which have to be taken into consideration.

*The Hodgson Kent Steam Meter.*—This meter is the outcome of the investigations carried out by Mr. Hodgson in perfecting air meters already described. The meters depend for their action on the law governing the volume of a steam which will pass through an orifice in a plate when impelled by a known difference in the pressures on opposite sides of the plate. The rate of flow of the steam varies as the square of the difference in pressure, and the simplest form of meter gives a direct indication of this rate of flow. If the pressure of the steam supply were to be kept constant, this indication would be a measure of the total energy of the steam passing. In practice, however, it is necessary to

make allowance for variations in the steam pressure, as with a higher pressure a greater amount of energy in the form of steam will naturally be passed through the orifice at a given difference of pressure. The meter described below automatically makes this correction, and an elaboration of this meter includes an integrator, which shows the total amount passed in a given period of time.

*Description of Meter.*—Dealing first with the orifice. This may take the form of a square-edged hole in the centre of a plate inserted in the pipe line, as shown in Fig. 121, or may be a plate projecting in, as in Fig. 126. Experience has shown that the most suitable pressure difference on opposite sides of the orifice is equivalent to a head of about

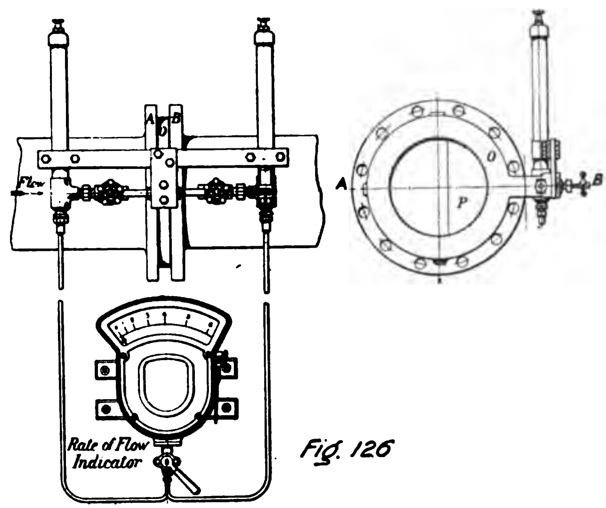



Fig. 126

50 in. of water. In order to provide this difference of pressure, the size of the orifice opening must depend on the maximum velocity of the steam in the pipe which has to be measured. This velocity may vary over wide limits, say from 85 ft. to 260 ft. per second. At the higher speed only a slight reduction in the area of the pipe is necessary to bring about the desired difference in pressure, and with a circular orifice the plate would be a mere ring protruding only very slightly into the bore of the pipe. Supposing that in these circumstances the plate were not very carefully positioned, or the jointing material not cut very nicely, the effects of the orifice on the flow of steam could not be relied upon. For these reasons the circular form of orifice is only adopted when a considerable restriction in the pipe is required. When the necessary restriction is less than half the cross-area of the pipe the orifice is arranged

as shown in Fig. 123, and as further reductions in the area of the plate are required the forms shown by the dotted lines adopted. The holes which communicate the steam pressures from opposite sides of the orifice plate to the meter are both brought as close to the plate as possible, for the reasons stated on page 114. It is assumed that the steam in the corner between the plate and its carrier has practically no movement, and that in consequence the exact form of the pressure holes is immaterial so long as they are in the proper position.

The restriction generally causes a drop in pressure of about 2 lbs. per sq. inch. Should the range of flow be greater than could be efficiently dealt with by one orifice plate, the device shown in Fig. 127 is used to avoid the necessity of changing the plates. It consists essentially of a short length of pipe containing a carefully constructed butterfly valve, which may be locked in various positions by means of an external sector.

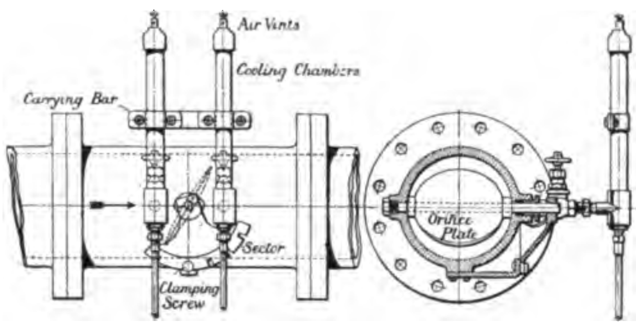


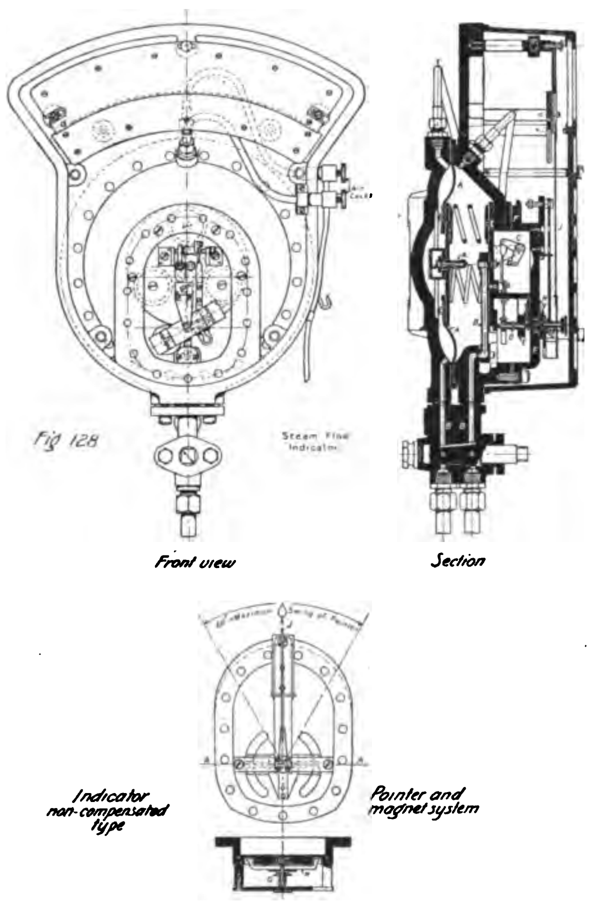

Fig. 127

The overall range of accurate measurement which can be obtained by the use of this device goes down to one-thirtieth of the maximum flow, as compared with a range down to one-quarter of the maximum which is all that can be accurately measured by a fixed orifice plate.

The two pressure passages in the orifice carrier communicate with a pair of condensing columns which are bracketed off the main pipe, as shown in Fig. 126. These columns ensure that the pipes leading to the metering instrument are kept absolutely full of water at all times, so that the readings shall not be affected by movements of the water surface in transmitting the pressure to the measuring apparatus.

*Indicator Non-compensated Type.*—The rate-of-flow indicator referred to already as the simplest form of meter depends for its action on the movement of a rubber diaphragm under the influence of variations in the difference of pressure on its opposite faces. The spaces on opposite sides of the diaphragm (Fig. 128) are in communication with the two

sides of the orifice plate in the steam pipe. A set of three coiled springs controls the movement of the diaphragm, which is communicated to a spindle $D$, through rods and a bell crank $C$. This spindle carries a powerful permanent magnet $E$. Outside the case and in line with $D$, there is another spindle $C$, carried in jewelled bearings, to which is attached an iron armature $H$, and the pointer $J$. In this way the movement of the diaphragm is transmitted to the pointer without it being necessary to make a water-tight sliding joint, and a very exact register of the most minute movements is thus obtained. The graduations on the dial over which the pointer works can, of course, be made to show the energy of steam passing at any predetermined pressure and temperature. At the bottom of the instrument there is a plug cock, by means of which the two sides of the diaphragm can be put in direct communication for the purpose of setting the pointer to zero, while air cocks are provided at the top to ensure that the diaphragm chamber is full of water.




*Recorder Non-compensated Type.*—When it is desired to make a permanent record of the steam flow, a modified form of instrument (Fig. 129) is used, although the orifice plate remains the same. Inside a cylindrical casing there is arranged a series of diaphragms similar to those of an aneroid barometer. The inside of these diaphragms is subjected to the lower steam pressure from the orifice, while the space outside the diaphrams is under the higher pressure. There is thus a tendency to collapse the diaphragms which is opposed by a helical spring attached to the

diaphragm spindle. The movements of this spindle are transmitted by a simple system of links to the pivot of the pen arm. The spindle which passes out through the wall of the pressure casing is kept tight by a leather-packed gland. A simple adjustment is provided on the arm operating the pen pivot. In the front elevation of the instrument (Fig. 129) it will be noticed that this arm is bent back on itself. The two legs of the U thus formed can be spread apart or drawn together by a pair of set screws, and the working length of the arm correspondingly regulated. The clockwork rotating the drum is of standard form, and the graduations of the paper are proportioned to give a direct reading of the quantity of steam flowing. The makers have devised a special planimeter in the construction of which a cam is incorporated in such a manner that by tracing round a record taken by one of these meters, the total quantity of steam measured during a given period can be given off direct.

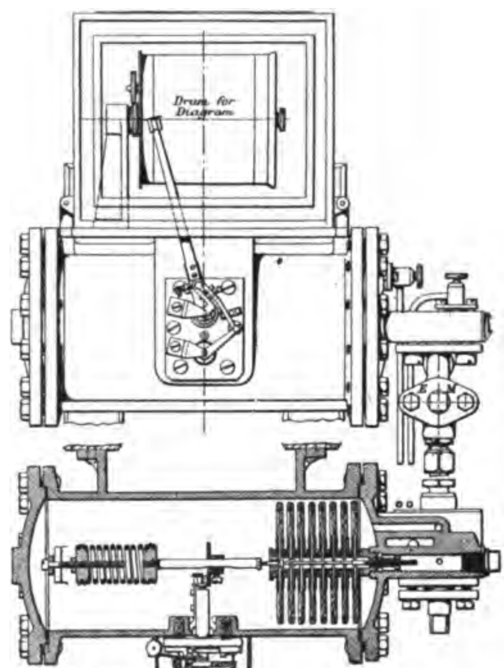


Fig. 129 Recorder non-compensated type

*Recorder with Pressure Compensating Device.*—The meters referred to so far do not take into consideration variations in the steam pressure. In cases where the pressure is liable to vary a correction must be made in the readings of the pressure difference across the orifice; if the amount of energy in the steam is to be metered, the arrangement illustrated in $F$ automatically makes this correction over a range in pressure of about two to one.

Fig. 130 is a general view of the instrument, whilst Fig. 131 shows the essential parts of the pressure correcting mechanism. The spindle which is operated by the aneroid diaphragms used to measure the pressure difference over the orifice is indicated at $A$. A crank and link connect $A$ with the pointer $B$ which pivots about $C$. The steam pressure in the main pipe is measured by a series of diaphragms—shown separately on the right, and is opposed by a helical spring. The rod $D$ trans-

mits the movement of the diaphragms to the pointer *E* and the lever *F*. We thus have two pointers, one indicating the rate of flow through the orifice and the other the actual steam pressure. The movements are combined and transmitted to a pen arm *C*, which consequently makes a graph repressing the energy value of the steam being metered. The combination of the two movements is affected by the link *H* and quadrant *J*.

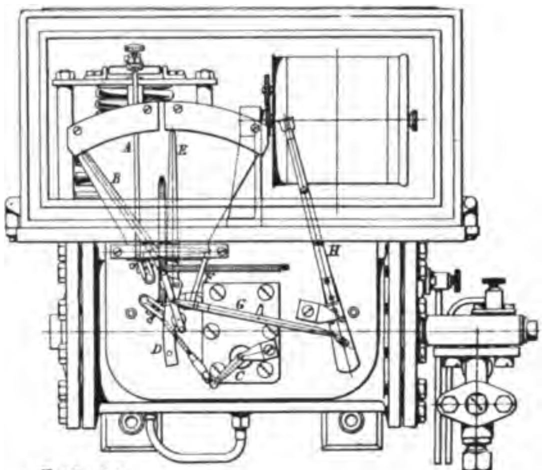


Fig. 130 Recorder with compensator complete (View of complete instrument)

In the positions shown in the sketch (Fig. 131) both the pointers *E* and *B* are at zero and the end of the link *H* is over the pivot *C*. The result is that the individual movement of neither of the pointers *E* and *B* will affect the pen arm *G*. If, however, the flow pointer *B* and quadrant *J* move round the pivot *C* an increase in the steam pressure will force down *F* and *H* and produce a movement in *G* which will vary in proportion to the movements of *E* and *B*. The various links are, of course, so proportioned that the resultant movement of the pen arm *G* is a true measure of the weight of steam passing the orifice, and consequently, assuming that the steam is saturated shows the energy being delivered. Even if the steam is super-heated, the instrument can be arranged to give a direct reading, but with a variable superheat a mathematical correction must be made. An accuracy within two per cent is claimed for the meter at full load, and four per cent at one-sixth load.

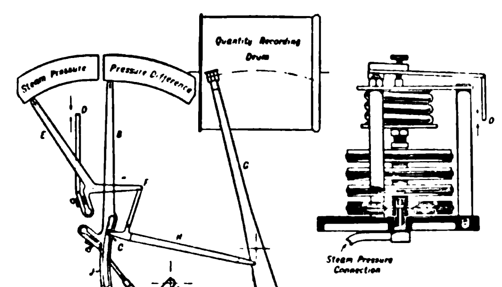



Fig. 131 Lever System of the compensated recorder Pressure boxes for compensation

### (*b*) The B.T.H. Steam Meter

In this steam meter a peculiar form of pressure head is employed for determining the velocity of steam in the pipe line. This consists

of a specially shaped pipe with its two openings in the path of the steam. The leading opening faces against the direction of flow, and the trailing opening faces in the direction of the flow of steam (Fig 132). The two openings are connected by a vertical U-shaped tube containing mercury. It will be observed that this is not a true form of Pitot tube, since a suction head is obtained at the trailing orifice and not the true static pressure at the point, consequently the velocity of flow is less than that given by the expression :

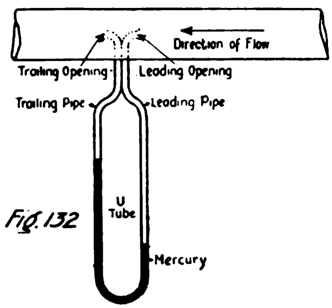



Fig. 132

$$p=\tfrac{1}{2}\rho V^2$$

The form of the equation cannot be predicted from theoretical considerations. But its advantage lies in the fact that the pressure difference obtained for a given flow is higher than that for the usual Pitot form. In practice the pressure head takes the form shown in Fig. 133, and is referred to as a nozzle plug. This nozzle plug is composed of a double conduit tube extending across the pipe diameter, each conduit having a separate set of openings. The leading set of openings extends the whole length of the tube across the pipe diameter, and faces against the direction of flow. The trailing opening is located midway between the ends of the tube at the centre of the pipe diameter, and faces in the direction of flow. The leading and trailing openings in the


Fig. 133

NORMAL VELOCITY NOZZLE PLUG FOR B.T.H. FLOW METERS.

normal velocity nozzle plug correspond to the single leading and trailing openings respectively in the elementary pressure head tube (Fig. 132).

It is said that since the leading set of openings in the nozzle plug extend approximately across the diameter of the pipe, the pressure transmitted to the meter is the mean of that due to the flow of steam across the section. It is difficult to see how this can be so, especially when the shape of a typical distribution curve (Fig. 114) is considered. Moreover, on the suction side there is only one hole, and this suction

pressure contributes an important amount to the indication. Individual calibration of each installation is desirable for accurate results.

The flow nozzle has drawbacks when the feed water supply to the boilers is dirty and the steam liable to cause scaling. Then the small passages or openings in the nozzle after a time become partially or totally closed up. Under these conditions the nozzle method is abandoned in favour of a constriction; this may be of the Venturi form or a shaped nozzle. When the velocity of the stream in the pipe line is too low to give sufficient head, a constriction is inserted in the pipe line to amplify the velocity at this point (Fig. 134).

Fig. 134

*The Recorder.*—The recorder (Fig. 135) consists of an iron casting, so designed as to form the limbs and well of a U-tube system and contains mercury. A by-pass valve is provided at the top of the meter to equalise the pressure at any time upon the U-tube system. A small iron float attached to the circular rack rests on the surface of the mercury in the small limb of the U-tube. The back engages a pinion mounted on a shaft carrying a horseshoe magnet, which has its pole faces near and parallel to the inside surface of a copper plug fastened in the body of the meter (see Figs. 136 and 137). The bracket supporting the rack and

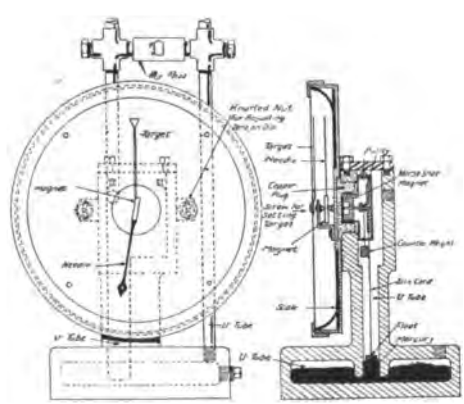


Fig 135 Diagrammatic sketch of movement

Fig. 135 General view of Steam flow indicator

pinion is made of copper, and all pivots, bearings, pinions and guide pulleys of a non-magnetic metal. Another horse-shoe magnet is mounted

on pivot bearings, with its poles near and parallel to the copper plug previously referred to, and with its axis of rotation in alignment with the shaft carrying the horse-shoe magnet inside the body of the meter. This element of the meter is shown diagrammatically in Fig. 136. This arrangement eliminates the use of a packing gland with its attendant friction. The indicating needle is attached directly to this outside magnet.

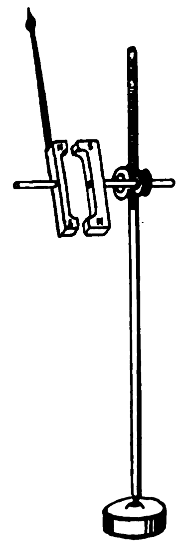


FIG. 136

In a simpler form of indicator the rack and pinion is replaced by a thread wound round a pulley, the magnetic transmission being otherwise identical. A difference of pressure in the nozzle plug is transmitted to the U-tube system of the meter and causes the mercury in the well to rise into the limb of the U-tube which contains the float. The instrument is made recording by adding a pinion to the shaft carrying the outside magnet, and this pinion engages a quadrant, the shaft of which carries the recording pen. The recording chart is concentric with the indicator dial and rotated by clock-work.

### (c) THE SARCO STEAM METER

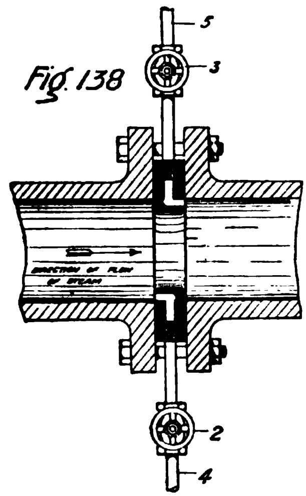
This meter utilises the pressure drop through a throttle disc and has a novel type of indicator invented by Gehre in 1907. The throttle disc (Fig. 138) has a round-edged orifice to which, as stated on page 115, there are theoretical objections. The indicator is illustrated in Fig. 139 and consists essentially of a cast-iron reservoir filled with mercury and water and having at one end a branch from which swings a hollow cone suspended on two springs. The high pressure side of the throttle disc is led into a mercury reservoir, which connects through a trunnion and tube, with the lower end of the hollow conical vessel, while the lower pressure is led through a similar trunnion and tube to the upper end of the cone. The cone is suspended by helical springs and with its tubes turns about the trunnions. The higher pressure, acting through the water in the connecting tubes upon the surface of the mercury in


Fig. 137

the box, will tend to drive this out into the lower end of the cone, thus causing it to sink. On the other hand, the lower pressure will act on the mercury in the cone and tend to force it back into the reservoir, so that the difference between the two pressures will determine the position of the cone. The shape of the cone and its position are such that its fall is proportional to the square root of the pressure difference.

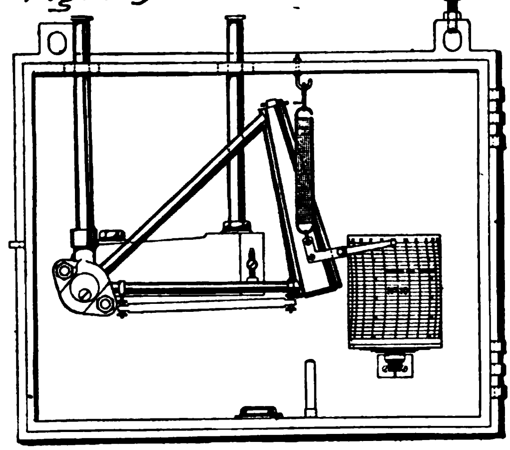
Since the weight of steam passing per unit time is proportional to the square root of the product of the pressure drop and the density of the steam, the scale of the indicator is a uniform one. The movement of the cone is transmitted to the recording pen by a lever mounted on a

Fig. 138




Throttle Disc in position.

Fig. 139



Recording Steam Meter without Pressure Compensator

fulcrum, which is free to slide in a slot cut in a fixed arm. The pen is placed at the top of an adjustable spring arm fixed to a vertical rod, the lower end of which is pivoted to the end of the lever, while the upper end is guided in a tube, so that the pen moves in a curved path. A vertical clock-driven drum is mounted behind the pen, and this carries the chart.

When it is necessary to take the account of variations of pressure in the steam main a modification of the instrument is employed in which the fulcrum of the pen lever is made to move so that the pen reading increases with the density of the steam. The high pressure side of the throttle disc is connected with an oil cylinder in which a piston moves against the resistance of a spring. The piston-rod is connected with one arm of a lever, the other arm of which carries a curved slot that engages with the fulcrum block of the pen lever ; this slot is so

formed that the pen movements due to the moving fulcrum are proportional to the square root of the density of the steam, so that both factors in the formula are introduced. The proportions of the throttle, levers, and scale are arranged so as to give the correct readings. A photograph of this form is shown in Fig. 140.

Figure 140.

Recording Steam Meter with Pressure Compensator

## SECTION IV

### The Calibration of Air and Steam Meters

The direct calibration of the large sizes of industrial meters by volume measurement in the case of air, and weighing the condensate in the case of steam, is necessarily an expensive and troublesome undertaking. Consequently indirect methods of calibration are much favoured. It has already been explained (page 104) that for the turbulent flow of any two fluids in a given channel or pipe if $\frac{V}{\eta}$ is kept constant where $V$ is the mean velocity, $\eta$ the kinematical viscosity[1] then the coefficient of discharge for any given pipe or channel is the same for these corresponding rates of flow for the different fluids.

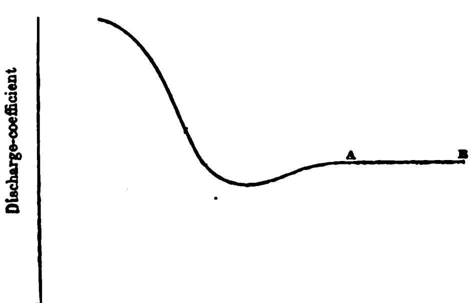



Fig. 141

For example, air and water; the kinematical viscosity of air is about thirteen times the value of that for water at the same temperature. Consequently the coefficient of discharge in a meter with water flowing at the rate of one foot per second would be the same as that found for air flowing at thirteen feet per second in the same meter. Hence this theoretical

[1] i.e. $\frac{\text{density}}{\text{viscosity}}$

relationship affords an extremely convenient method of calibrating very large meters. The general form of the curve connecting coefficient of discharge with variations of velocity, density, and viscosity is shown in Fig. 141, the coefficient of discharge being plotted as ordinate and $\frac{V}{\eta}$ as alscissae.

The importance of making comparisons at identical values of $\frac{V}{\eta}$ was pointed out by Dr. Stanton, and it will be evident from a consideration of Fig. 141, that since the coefficient of discharge varies with the value of $\frac{V}{\eta}$ in making comparisons between two fluids of kinematical viscosities $\eta_1$ and $\eta_2$, it is essential that $\frac{V_1}{\eta_1}=\frac{V_2}{\eta_2}$

It is possible, however, at high velocities, for the coefficient of discharge to remain constant for a considerable range of $V$, as shown by

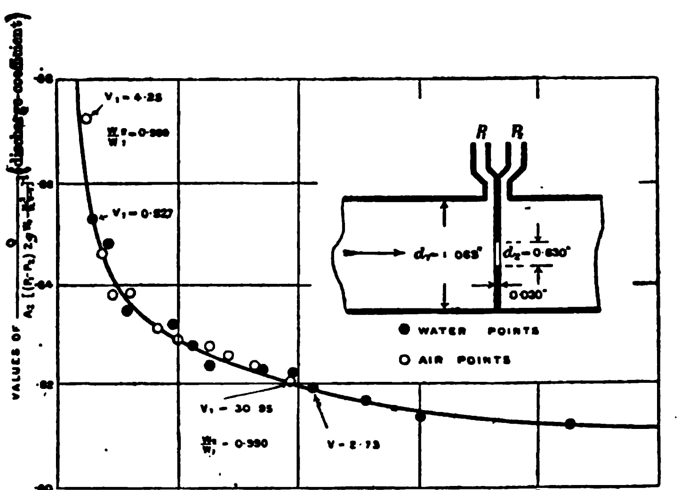



Fig. 142

the horizontal $A$ $B$ of the curve, when one or two values of the coefficient will suffice for the range employed. It is essential when calibrating with water to employ a range of velocities for the water which correspond (on the $V$ basis) with those which will be encountered in practice when the meter is employed for gas, i.e. the water velocities must be one-thirteenth those of the air. Experimental results confirming this generalisation are shown in Fig. 142.[1]

[1] Fig. 142. It will be observed that Hodgson's symbol $\frac{VW}{\mu}$ corresponds to velocity divided by the kinematical viscosity of the air or water on the up-stream side of the orifice: $V_1$ being the velocity in ft. per sec., $W_1$ the weight of fluid in lbs. per cu. ft., and $\mu$ the coefficient of viscosity.

In the above expression it will be observed that density enters into the value of the kinematical viscosity and Hodgson has pointed out that in the case of orifice meters, when there is a considerable pressure drop across an orifice the density on the two sides will not be the same and consequently there will be a deviation for big pressure difference. This has been experimentally demonstrated by him, the result being shown graphically in Fig. 143. It might be remarked, however, that a large pressure drop through the meter is very unusual and implies inefficient design.

The above described method of calibrating large meters for air and steam by means of experiments with water flow is very generally employed in practice. Hodgson gives the following comparative data for

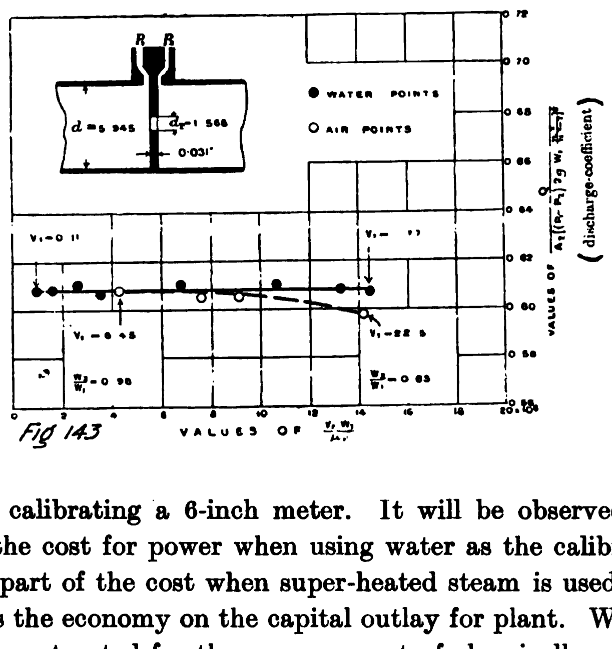



Fig 143

the cost of calibrating a 6-inch meter. It will be observed from the table that the cost for power when using water as the calibrating fluid is only $\frac{1}{315}$ part of the cost when super-heated steam is used. In addition there is the economy on the capital outlay for plant. When meters have to be constructed for the measurement of chemically active gases, such as chlorine, the advantages of a water calibration are obvious.

### Comparison of Power required for Various Types of Calibration Plants.

The following Table gives, according to the type of calibration plant used, the approximate power in kilowatts required for testing a 6-inch meter, which has a capacity of 6 lbs. of air per second at 80 lbs.

per square inch (abs.) and 60° F., and which causes a friction drop of 1 lb. per square inch in the main.

The Table has been calculated on the following assumptions :—

(*a*) That where the meter is calibrated in a closed circuit, there is an additional fall of pressure of 1 lb. per square inch due to friction in the circuit ;

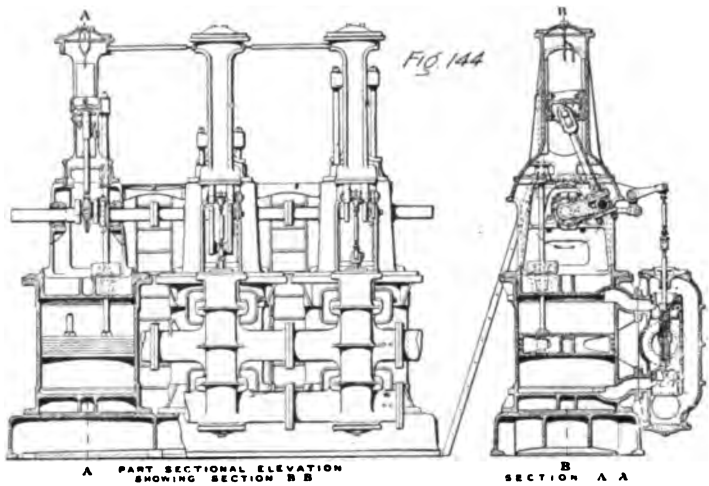
(*b*) That the efficiency of the compressing or circulating plant is 0·64 ;

(*c*) That 20 lbs. of steam, if used for the purpose of producing power instead of for the purpose of calibrating meters, would produce 1 kilowatt-hour.

| | | Killowatts. | Relative Figures. |
|---|---|---|---|
| I | Discharging steam at 80 lbs. per square inch (abs.) and 100° superheat through the meter and a valve into a condenser | 666 | 925 |
| II | Discharging air at 80 lbs. per square inch (abs.) through the meter and a valve to atmosphere . . . . . . | 598 | 830 |
| III | Discharging steam at 20 lbs. per square inch (abs.) and 100° superheat through the meter and a valve into a condenser | 348 | 483 |
| IV | Circulating air at 14·7 lbs. per square inch (abs.) in a closed circuit . . . . | 20·63 | 28·6 |
| V | Circulating air at 80 lbs. per square inch (abs.) in a closed circuit . . . . | 8·82 | 12·2 |
| VI | Circulating water in a closed circuit . | 0·721 | 1 |

*Calibration Apparatus of the Displacement Type.*—The Rand mines, South Africa, have the most comprehensive system of air metering appliances in the world, and owing to the magnitude of the total changes —a difference of one per cent on the total registration is equivalent to £3000 annually—for power based on the indications of the various meters it was deemed advisable to instal an elaborate calibration plant of the displacement type. This plant is now the standard air calibration plant for South Africa. The air to be measured is passed through a large displacement meter (see Fig. 144), which is built somewhat on the lines of a steam engine. It has three vertical double-acting cylinders 36 inches in diameter, and the stroke is 27 inches. The admission and discharge of the air to the cylinders are controlled by means of piston values which are set to cut off exactly at the top and bottom of the stroke. It has two piston rods per cylinder. The con-

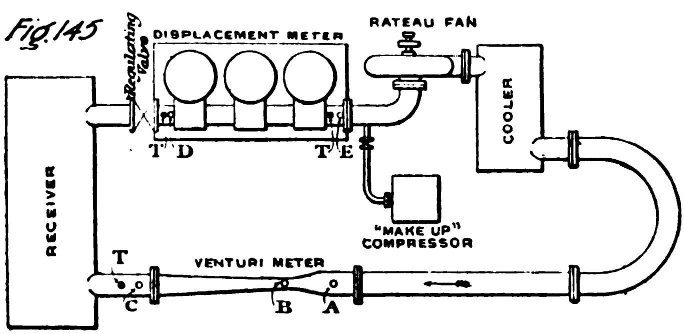
necting rods are inverted and a three-throw crankshaft is mounted close to the cylinder cover, as in the old type of marine engines. The valves are operated by simple link motion, since it does not require the usual cut off and reversing gear. The stroke volume is 95·156 cubic feet and the meter passes roughly one ton per minute of air at the maximum speed at which it is designed to run.




This displacement meter forms part of a closed air circuit, wherein the air is circulated by a Rateau fan producing a pressure difference of about 2·5 lbs. per square inch when the air is at a pressure of 100 lbs. per square inch. The pressure in the circuit is maintained by a small "make up" compressor connected as shown in Fig. 145.

The air is passed through a cooler so as to obtain a steady temperature, and then through the meter under test and the displacement meter. The displacement meter operates in precisely the same manner as a reciprocating engine with a small pressure drop of less than 2½ lbs. to overcome the friction of the mechanism.

Fig. 145



## SECTION IV

### ELECTRICAL TYPES OF GAS METERS

Besides the above-mentioned mechanical types of gas meters a number of novel forms based on electrical measurement have been developed in recent years, and one at least of these has been made on a commercial scale.

*The Thomas Gas Meter.*—This meter was invented by Professor Carl C. Thomas, of the University of Wisconsin. It is based on the measurement of the heat required to raise the temperature of the gas through a known range of temperature.

The electrical energy required to produce the change in temperature is measured, and, as is shown later, is proportional to the weight of gas flowing.

Electrical resistance thermometers are used to regulate the temperature range through which the gas is heated, because with thermometers of such type very small differences of temperature can be accurately determined.

If $E$ is the amount of energy required to raise the temperature of $Q$ units of weight of gas through $t$ degrees, and if $s$ is the specific heat of the unit of weight at constant pressure, then

$$Q=\frac{E}{ts}$$

In this meter the heater unit has its resistance material distributed over the section of the passage so that all of the gas is heated. The resistance thermometer screens are likewise distributed over the passage, so that the average temperatures of the gas is obtained.

The arrangement of the circuits of this meter are shown diagrammatically in Fig. 146.

Within the pipe is an electric heater unit between two electric thermometer units $T_1$ and $T_2$. The heater consists of spiral turns of bare resistance wire wound around a conical supporting frame so that heat is dissipated over the section of the pipe. In the heater circuit is a rheostat for regulating the electrical energy supplied to the heater and the instruments for measuring this energy.

The thermometer units form two arms of a Wheatstone bridge, the other two arms being fixed coils of wire that have a zero temperature

coefficient. Across the Wheatstone bridge is a galvanometer, and in series with one thermometer is a small rheostat for balancing the bridge.

In series with the entrance thermometer is also a small resistance $R_{T1}$ equal in value to the increase in resistance in the exit thermometer for a rise in temperature of about 2° Fahr. (in this particular case 2·024°).

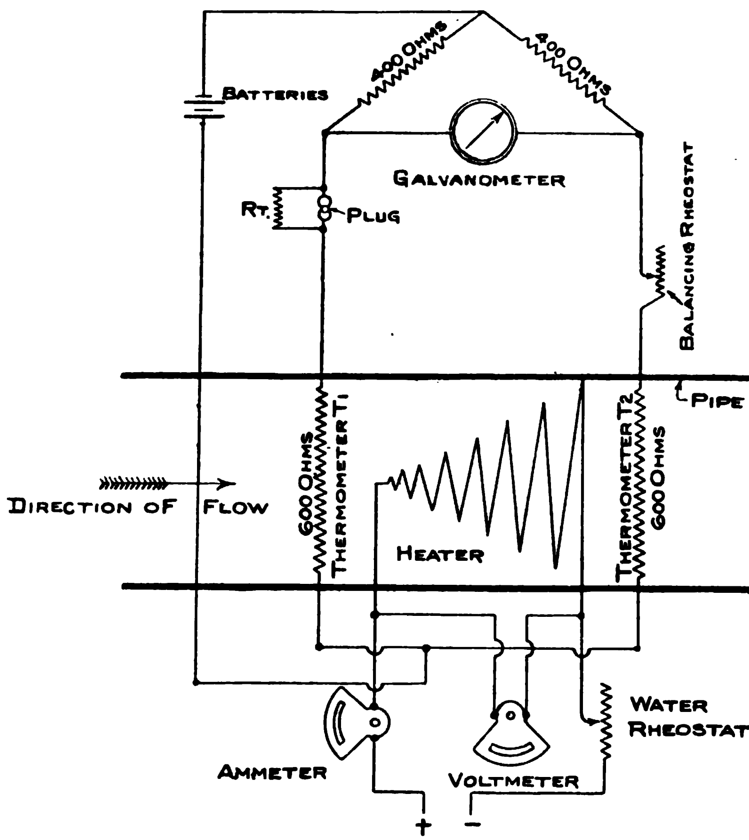



DIAGRAM OF ELECTRIC METER CONNECTIONS.

*Fig. 146*

This temperature difference resistance is arranged so that it can be conveniently short-circuited.

The operation of this meter is as follows : With gas flowing through the meter, but with no energy in the heater, and with the temperature difference resistance $R_T$ shorted out, the two thermometers are brought to exact balance by means of the balancing rheostat and the galvanometer. Then the resistance $R_T$ is cut in and sufficient electrical energy

is supplied to the heater to bring the galvanometer to a balance again; that is, sufficient electrical energy is supplied to bring the exit air or gas to a temperature two degrees higher than that of the entering gas, regardless of the absolute temperature of the entering gas. The electrical measuring instruments in the heater circuit then indicate the energy required to raise the temperature of the gas through a known range.

It will be observed that this meter measures the rate of flow in weight units and not volumetric units. So long as the specific heat is constant the meter is independent of pressure and temperature changes in the gas.

*Conditions which affect Specific Heat.*—It is well known that the specific heats at constant pressure of the permanent gases such as air, nitrogen, hydrogen, are independent of the pressure within ordinary working limits.

Variation in chemical composition of the gas will, however, affect the specific heat. For the small variations in composition encountered in normal working the effect on the specific heat is small and can be allowed for if the composition of the gas is ascertained. The percentage of water vapour present has also an appreciable influence since the specific heat of water vapour is approximately twice that of air.

In any case, each particular installation requires a calibration since distribution of velocity over the cross-section of the pipe is dependent on local conditions, such as proximity to bends, etc., and it is only under certain ideal conditions that it is possible to obtain the coefficient of the meter by calculation.

*Commercial Form of Thomas' Meter.*—In its original form the meter worked on the principle of supplying a known constant energy to the gas and of graphically recording the resultant rise in temperature. In its later commercial form it automatically maintains a constant temperature increase in the gas and measures the energy required to produce this increase. Temperature difference on the two sides of the heater can be maintained constant to a sufficient accuracy by a simple device in connection with resistance thermometers which regulates the electric energy in the heater. Since the specific heat of a unit weight of the gas remains constant for small variations of temperatures and pressure, and since the temperature rise is maintained constant, the weight of gas flowing must be directly proportional to the electrical energy dissipated in the heater. Thus with this meter the only quantity necessary to be measured is electrical energy, and this can be done by means of well-developed commercial wattmeters of either the graphical or integrating type. Also,

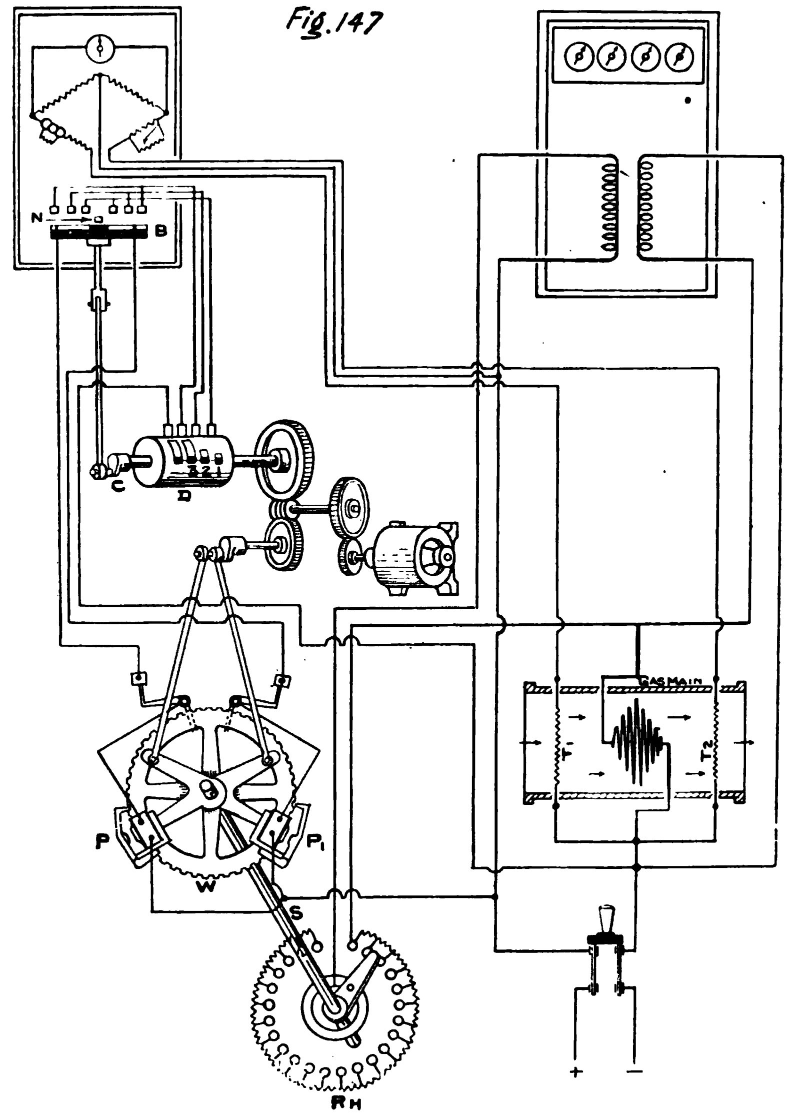
since the weight of gas is directly proportional to this electrical energy, the wattmeter dials may be made to read directly in standard cubic feet at any desired pressure and temperature.

Thus this method lends itself easily to a commercial design that gives continuous results in either graphical or integrated form, directly in standard units, and without the necessity of calculation.

Fig. 147 is a diagrammatic sketch of the commercial form of the meter. It differs from the manually controlled meter only in that it is provided with an automatic device for maintaining a constant temperature difference in the gas on opposite sides of the heater unit. An increase in rate of flow of gas through the meter will cause the thermometer $T_2$ to become less than its normal two degrees warmer than thermometer $T_1$. This decreases the resistance of $T_2$ with respect to $T_1$, and causes a deflection of the galvanometer needle $N$ to the right, the amount of the deflection depending upon the amount of change that has occurred in the rate of flow. On the shaft $S$ of the rheostat $Rh$, which is in series with the heater, is a toothed wheel $W$. At the right and left edge of this toothed wheel two pawls, $P$ and $P_1$, move with a continuous reciprocating motion through an arc having the length of three teeth on the edge of the wheel. A one-eight horse-power motor on the front of the panel runs continuously at constant speed and drives the bell-cranks carrying these pawls. It also drives a contact drum $D$ and a crank $C$, which causes a bar $B$ to clamp the galvanometer needle $N$ at intervals of a few seconds between a series of metallic contacts. If the change in gas flow has deflected the galvanometer needle so that it is clamped between the right-hand upper and the lower contact, the pawl $P_1$ will engage the toothed wheel when segment No. 3 on the revolving drum engages with its contact finger and energises the magnet on $P_1$. This contact will occur when the pawl is at the bottom of its stroke, and the drum segment will keep the pawl engaged until it reaches the top of its stroke. Thus the deflection of the needle three divisions to the right has caused the rheostat arm to be moved so that the heater energy has been increased three steps. Had the flow of gas decreased, the deflection of the needle would have been to the left and the heater energy would have been decreased. Had the deflection of the needle been only two divisions, the heater energy would have been changed two steps, etc. So long as the gas flow remains constant the galvanometer needle remains balanced and the heater energy remains unchanged. Thus the energy in the heater is automatically regulated to maintain a constant temperature difference of about 2° Fahr. in the gas. This accomplished, it only

remains to measure the electrical energy in the heater, which is done by an integrating wattmeter, as shown in the diagram, or by a graphical wattmeter which traces on a record roll a continuous curve showing the

Fig. 147



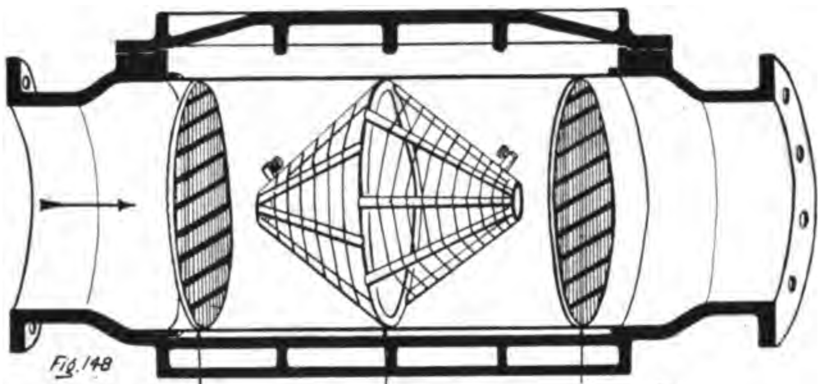

Diagrammatic sketch of automatic electric meter.

rate of flow of gas at any time. Since the weight of gas flowing through the meter is directly proportional to the watts dissipated in the heater, the wattmeters can be made to read directly in any standard weight units.

Fig. 148 is a sketch of a typical installation, in which the resistance

wire is wound on a double-ended cone, while the thermometers are in the form of two screens distributed over the area of the pipe. The thermometer and heater units are assembled in an inner casing, around which is a gas-jacket to reduce loss of heat.

*Cost of Operation.*—With this electric meter about one kilowatt-hour of energy is required to measure 75,000 cubic feet of free gas. Assuming that one kilowatt-hour can be obtained from 50 cubic feet of gas, the cost of operation of the meter is equivalent to less than one-tenth of 1 per cent of the gas that it will measure. As this percentage is well within the limit of the possible accuracy of measurement, the cost of operation is seen to be moderate.




*The King Meter.*—A totally different type of electrical meter is that proposed by Professor L. V. King, of McGill University, Montreal. This meter is based on the use of the linear hot wire anemometer.

It has been proved that the heat loss from a wire maintained at constant temperature in a gas stream depends upon the product (density and square root of the velocity) and on the specific heat, thermal conductivity, and to a small extent viscosity of the gas.

Now the specific heat is practically independent of pressure and temperature for a gas of constant composition, while the thermal conductivity and viscosity are independent of the pressure and only vary comparatively slowly with temperature over such a range as would probably be met with in practice.

Consequently, for most practical conditions the indications of the anemometer will depend upon the product of the density and the velocity as in the case of the Thomas meter above-described.

Essentially the hot wire anemometer consists of a platinum wire

heated electrically to a certain excess temperature above the surrounding gas. The experiment shows that the heat loss from the wire is proportional to the square root of the velocity of the stream past the wire or expressed mathematically,

$$W = B\sqrt{V} + C$$

where $W$ is the heat loss per unit length.

$B$ and $C$ are constants for a given wire and temperature excess.

In practice the procedure is to maintain the wire at a definite resistance, and hence a constant temperature by varying the electrical current through it. The value of the current is then an indication of the stream velocity.

When applied to measure the velocity of the stream of gas passing

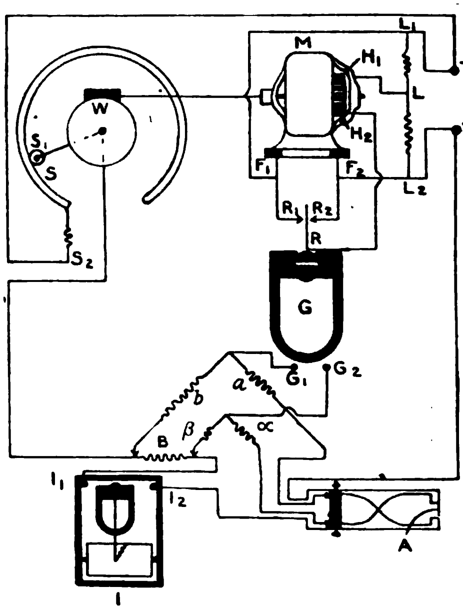
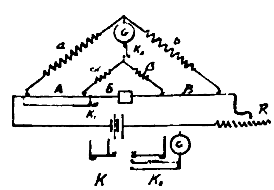



Fig. 149




along a pipe it is desirable to employ an automatic arrangement for varying the circuit so as to obtain a continuous record of the current easily interpretable in terms of gas velocity.

One method of effecting this is shown diagrammatically in Fig. 149.

A brass plug (Fig. 150) is inserted into the pipe and carries a block of insulating material. Fastened to this insulating portion is a stiff framework of narrow, thin steel strips, bent in the form of a U, serving both to protect the wire from injury as well as to carry the current to the anemometer wire from one of the terminals $C_1$. The other current

terminal $C_2$, and the potential terminals $P_1$ and $P_2$, are disposed as shown in the diagram.

In order to make the readings of the flow as given by the recording apparatus independent of temperature fluctuations in the gas, it is only necessary to construct the ratio-coils $a$ and $a$ of the Kelvin double bridge of a wire or a combination of wires having the same temperature coefficient as the anemometer wire, and arrange to have these coils exposed to the gas whose flow it is desired to measure.

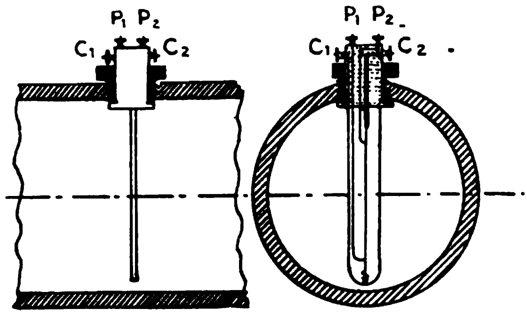



Fig. 150

*Description of Recording Meter.*—The resistance $S$ of the adjustable rheostat may be automatically adjusted so that the galvanometer $G$ is always balanced, while the current $i$ through the anemometer-wire is registered on a recording ammeter $I$, giving a record easily interpretable in terms of wind-velocity. The moving contact of the rheostat, $S_1$, is attached to an arm which can be caused to rotate in either direction by means of a worm-gear $W$ connected to the shaft of a small direct-current motor $M$, whose field $F_1F_2$ is permanently connected across the line terminals $T_1T_2$. Across the terminals $T_1T_2$ are inserted in series two equal high resistances $L_1L$ and $LL_2$ : one of the brushes is connected to $L$ and the other to the movable pointer $R$ of a sensitive galvanometer-relay $G$ ; the terminals $L_1$ and $L_2$ are connected to the contacts $R_1$ and $R_2$. The remainder of the apparatus corresponds to the connections shown in small figure on the right, the galvanometer $G$ being replaced by a galvanometer-relay and the ammeter by a recording instrument. The mode of operation of the recording anemometer can be easily followed from Fig. 149 : when the anemometer-wire undergoes a change of temperature, and therefore of resistance, due to a change of gas-velocity, the galvanometer is thrown out of balance and contact is made with one or other of the terminals $R_1$ or $R_2$ ; current is allowed to pass through the armature of the motor $M$ in one or the other direction, thus causing

a corresponding rotation of the shaft and worm. The direction of rotation is so arranged that the resistance $S_1S_2$ is altered in such a way that the movable contact $R$ of the relay-galvanometer is brought back to the position of no contact.

## SECTION V

### Liquid Level Indicators

The time-honoured method of indicating the level of liquid in tanks is of course the gauge-glass. This consists simply of a glass tube communicating at its upper and its lower end with the top and the bottom of the tank. The method is universal in the case of steam boilers, and has been tried on the fuel tanks of aircraft and motor vehicles, but owing to the varying inclination of the tanks, particularly in the case of aeroplanes, the indicator rarely gives an accurate estimation of the contents. Moreover, the fragile nature of glass is a serious consideration where inflammable liquids are concerned.

Fig 151

*Float and Rod Gauge.*—Level gauges based on the use of floats have been devised in a variety of forms. Probably the simplest example is that shown in Fig. 151. The vertical tube contains a rod free to move up and down with a pointer at the upper end, and a float at the lower. Changes in level are transmitted directly to the pointer. This device is of course only applicable to shallow tanks, and would become very cumbersome if applied to deep tanks.

*Float and String System.*—Another method which is almost as elementary in principle is the float and string instruments. This was a standard fitting on enemy aircraft during the War.

The float of the gauge was suspended by means of a silk cord, which winds on the pulley of the gauge proper. The pulley is under such a tension as to nearly balance the weight of the float in air. Therefore, as the surface of the liquid rises or falls, the pointer will show the position of the float in the tank. The float is guided by an upright cylinder which keeps it from swinging about in the tank. The pointer is connected to the pulley through cog-wheels. Since the effective force producing the motion of the pointer is very small, the slightest binding of the gears may cause error. A sketch of the arrangement is shown in

Fig. 152. The capacity of the float used for short transmissions is about 3 cubic inches, and for long transmissions, of 10 feet or more, the float is made larger and about 8 cubic inches. For deep tanks the pointer of the indicator is arranged in a novel manner to travel through several complete revolutions and a spiral curve by means of a small rack and pinion.

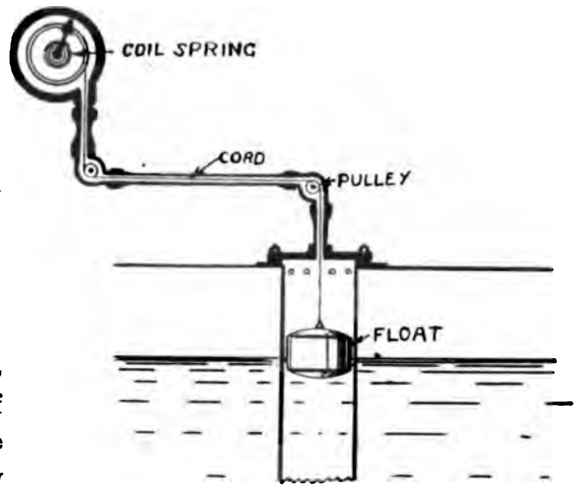



Fig. 152

A photograph of the dial is shown in Fig. 153, whilst Fig. 154 is a diagram of the spiral mechanism. The pointer is free to slide radially in the boss of the pulley, but rotates with it. Fixed to the back of the case and projecting through the pulley is a small pinion which engages with a rack fixed to the pointer.

As the string coils or uncoils on the pulley the rack rolls round the fixed pinion, thus moving the pointer in or out radially a distance proportional to the pitch circle of the pinion for each revolution.

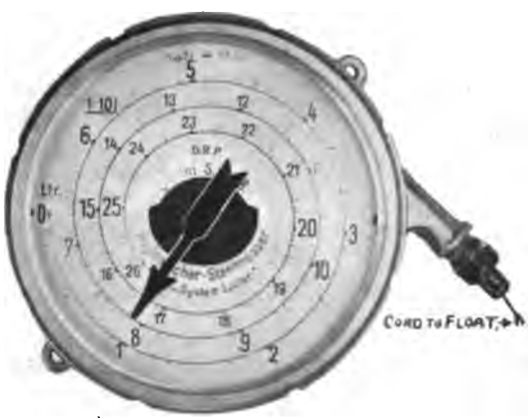



Fig. 153

The float and string system, although very simple in theory, becomes elaborate and complicated in practice, since pulleys must be arranged at each bend, and both the tube and instrument must be air-tight.

*Float and Eccentric Rod.*—Gauges depending upon simple mechanical arrangements for converting the movement of a float into indications on a dial fixed to the tank are also largely used. One form of this class of instrument is shown in Fig. 155. The rod $A$ is free to rotate, through an arc about the pin $C$ at the bottom, and carries the pointer or a cog-wheel

at its upper end. The movement of the float $F$ under the influence of the liquid causes the rod to turn since the float forms a connecting link between the rod $A$ and the fixed rod $B$. The angular rotation of the rod $A$ is, of course, limited to less than 180°, but the pointer is sometimes geared to give a longer scale. This instrument is light and fairly satisfactory in use.

*Float and Twisted Strip.*—A more elaborate form of instrument is shown in Fig. 156. The float is guided by two rods. A twisted pinion wire, passing through a nut in the float, converts the linear motion of the float to angular rotation of the pointer. The pointer can in this case turn through a complete circle without the use of gears. When the instrument is used in pressure tanks, where air is employed to force the liquid out, the glass front of the indicator has to be made air-tight.

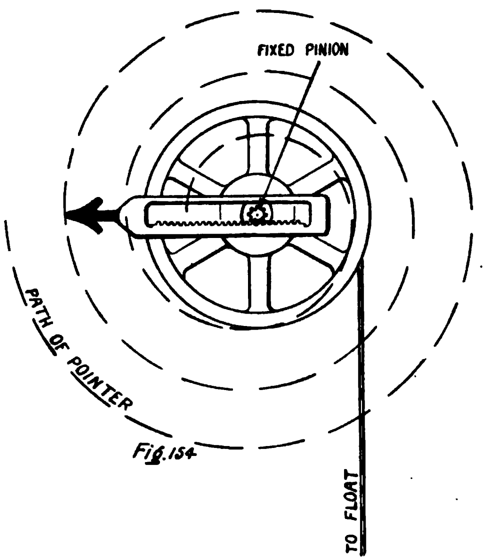



Fig. 154

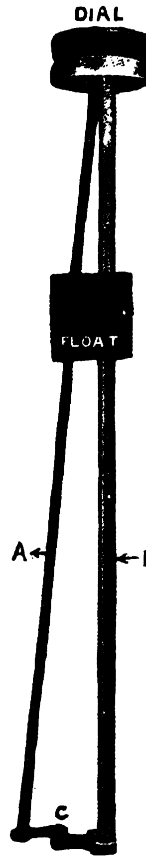



Fig. 155

To avoid this necessity, the gauge may be worked magnetically as follows : The twisted rod carries at its upper end a magnet which rotates with the rod, and actuates a magnetised steel pointer pivoted on the other side of a thin metal partition forming the wall of the tank. This avoids all glass to metal pressure joints, but detracts from the accuracy of the indication. This magnetic device was first used by Müller in 1886, and has since found considerable application, such as in the steam meters already described (pages 122 and 127).

*Float on Pivoted Arm.*—A novel gauge differing slightly from the above and employing the magnetic pointer is shown in Fig. 157. This consists simply of a small float moving through a circular arc at the end of a rod. The scale is not uniform, and the float and arm require a considerable amount of space. The same disadvantage is met with to some extent to all float methods, and is particularly felt in the case of aircraft tanks which are elaborately stayed and stiffened internally. In fact, the tanks have generally to be specially designed with a view to accommodating the gauge to be used. These appliances are rarely regarded as accurate quantity measuring devices owing to the back-lash, friction, and variable immersion of the float. Generally, they are classified as indicators graduated in fractions such as $\frac{1}{4}$, $\frac{1}{2}$, and full. The last few gallons of liquid cannot usually be observed.

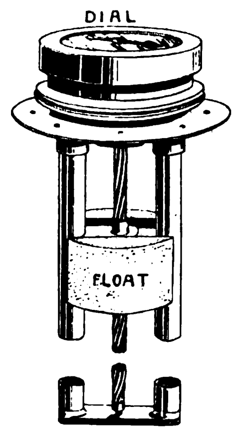



Fig. 156

### Pneumatic Gauges

Quite a number of instruments have been devised to transmit indications of depth by the aid of air pressure.

*Air Pump Method.*—One type of instrument employs a small pressure pump to force air through the liquid by means of a pipe dipping to the bottom of the tank. The head required to effect this measured on a pressure gauge. A sketch of the method is shown in Fig. 158. Each time a reading is

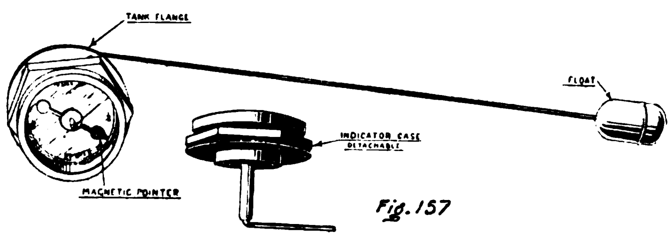



Fig. 157

required the hand pump is operated until the liquid is blown out of the vertical pipe in the tank, and the reading on the gauge taken immediately afterwards. The defect of this method is the inconvenience of pumping up for each reading, and the fact that the leakage back through the pump valve, etc., causes the pressure to fall rapidly. The reading has usually to be taken within a few seconds.

*Tide Gauge.*—An interesting application of the above principle is the tide recorder of Field and Cust developed by the Cambridge Scientific Instrument Company. In this instrument the height and frequency of

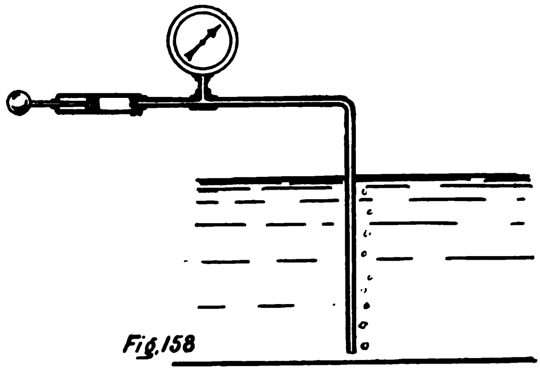


Fig. 158

the tide at a station on the coast is continuously recorded on a chart. The recording portion of the instrument is placed at a sheltered spot inshore, and a pipe laid out and anchored in the sea where the tide record is required. A small but continuous stream of air escapes from the open

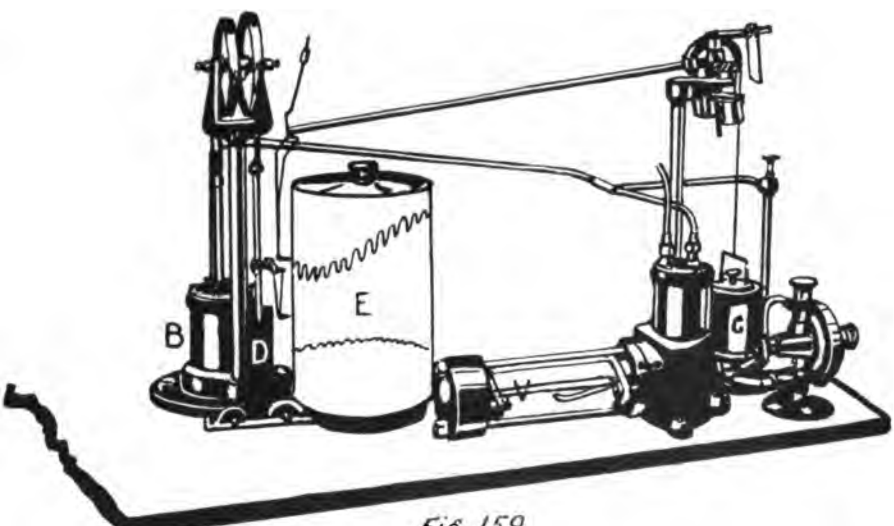



Fig. 159

end of the pipe, and the instrument on shore graphically records the pressure in the pipe, which pressure is equal to the hydrostatic head over the open end of the pipe.

A general view of the instrument is shown in Fig. 159. Below the recording apparatus, and forming a stand for it, is a reservoir of air compressed to about 150 lb. per square inch. This air is allowed to

escape through a reducing valve into a pipe, one end of which leads to the top of a vessel $A$, containing mercury (see Fig. 160), whilst the other end is anchored on the bottom of the sea, at the point where the variations of tide are to be recorded. Air is allowed slowly to escape from the open and anchored end of the tube, a single charge of compressed air sufficing to run the apparatus for fifteen days.

As the tide rises and falls the head of water over the open end of the pipe varies. The pressure of the air in the pipe and the vessel $A$ varies correspondingly, and forces more or less mercury into the float-chamber $B$, thus rising or lowering the float $C$. From this float a thin steel band

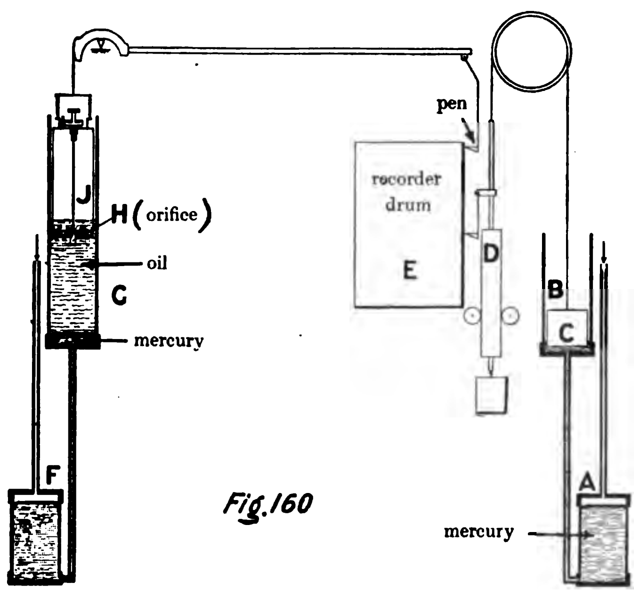



Fig. 160

passes over and is attached to a pulley mounted on a horizontal shaft. A second pulley on the same shaft supports by a similar band a pen carriage $D$ and a counter-weight to the float.

This arrangement of two pulleys facilitates the adjustment of the motion of the recorder pen to the scale of the chart on which it works. This chart is carried by the clock-driven drum $E$.

All the air passing to the immersed end of the pipe has first to bubble through water contained in the horizontal glass cylinder $V$ visible in the front of Fig. 159. This at once renders evident any accidental clogging-up of the under-water escape. The apparatus described above traces the long-period tide.

Superimposed on this, however, may be short period oscillations of

secondary tidal waves. A separate record of these on an enlarged scale is obtained by means of the apparatus shown to the right of Fig. 159. The vessel *F* (Fig. 160) is also in communication with the air supply.

The varying air pressures are accompanied by corresponding alterations in the level of the oil floating on the top of the mercury in the float-chamber *G*. The bottom of the float *J* in this chamber is provided with an adjustable orifice *H*, through which oil can flow into or out of the interior of the float, which is balanced so that it always tends to maintain its mean position.

In the case of the ordinary 12½-hour tide, the alteration of the level of the oil takes place so slowly that the liquid flows in and out of the float at a rate sufficient to enable the float to maintain its mean position. The

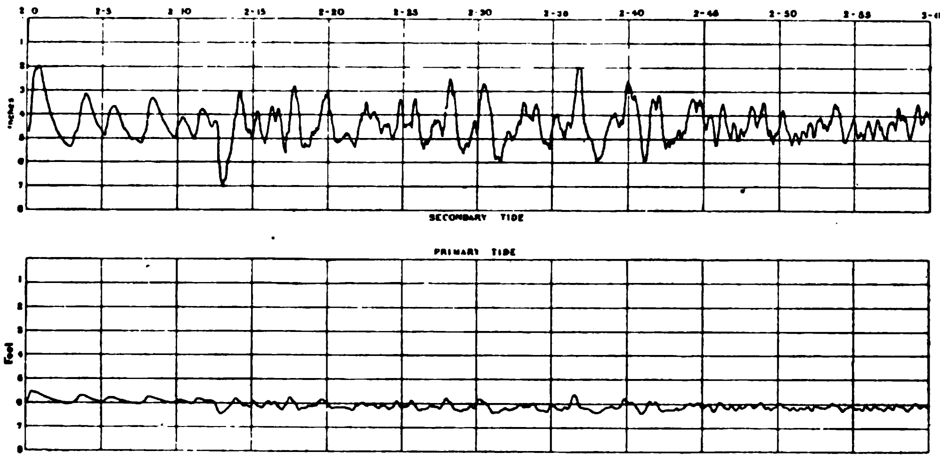



*Fig 161*

variations of level due to the secondary tides being much more rapid, the oil is unable to pass with sufficient freedom through the orifice to keep its level the same both inside and outside the float. The latter, therefore, rises or falls in conformity with the secondary tides, and its motion is transferred by a multiplying lever to a pen which makes a record of this secondary tide on the upper portion of the chart borne by the drum of the recorder.

Fig. 161, which was obtained at Christmas Island, Polynesia, with the double recorder, brings out the type of record for the secondary tide. This record was taken during a storm, and although the maximum movement recorded on the primary tide was only 10 inches (25·4 cm.), yet the secondary tide record shows a movement of 5 inches (12·7 cm.), the waves having a wave length of about half a mile.

Tide records provide valuable data for use in the accurate prediction of tides. It is well known that the fluctuations of the sea may be expressed by a series of tidal harmonic components due to the action of the sun and moon, ellipticity of the lunar orbit, the moon's motion out of the Equator, and so on. The constants of all these tidal constituents can be determined by the harmonic analysis of the tide gauge records for the port in question. That is to say, the amplitude of each harmonic constituent and its phase relationship with all the others can be found.

The information thus obtained can then be utilised in what is termed a tide predicting machine to predict the tides for the port, and the well-known tide-tables are based upon these predictions.

*Air Vessel Method.*—Another form of pneumatic instrument, which has been tried on motor vehicles, consists of a large air vessel fixed to the base of the tank, and connected to a pressure gauge. The changes of hydrostatic pressure due to variations in liquid level are transmitted by the air column to the gauge. A sketch of the method is shown in Fig. 162. The air vessel must have a large diameter to minimise the changes of level due to the compressibility of the air. In the case of pressure tanks the gauge is arranged differentially, so as to indicate the difference of pressure between the top and the bottom of the tank. The gauge and its connecting tubes must be absolutely airtight, but even then the air will slowly disappear by solution in the liquid, etc.

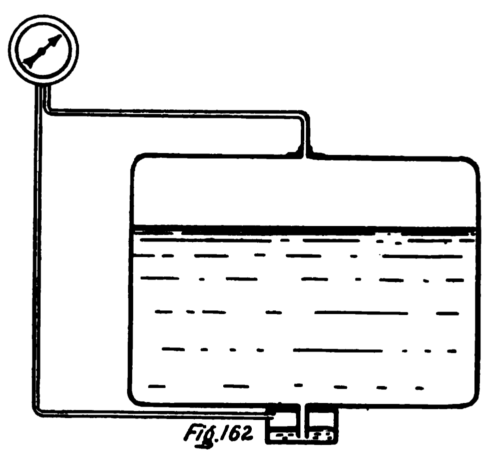


Fig. 162

An additional source of trouble is condensation of the vapour with the formation of air-locks in the pipe.

The design of a suitable pressure gauge for any pneumatic level indicator presents practical difficulties. The maximum pressure-head in the case of the general run of tanks is only a pound or two per square inch at full scale. Bourdon tube gauges cannot be made with sufficient sensitivity, whilst silk diaphragm gauges invariably leak slightly. Well-made metal diaphragm gauges are probably the most satisfactory.

A typical form of low pressure gauge is shown in Fig. 163. A battery of aneroid capsules is connected to the pressure pipe leading to the bottom of the tank, while the interior of the case containing the capsules

is in communication with the static pipe to the top of the tank. The motion of the diaphragm, under the pressure difference, is transmitted by means of a quadrant and gear-wheel to the pointer. A peculiar feature of the instrument is the control spring; this is soldered to the edge of each capsule. The tendency of the capsules under pressure is to open out fan-wise, curving rather than elongating the spring, and by this device greater sensitivity is obtained.

The average accuracy of the instrument itself is not great, owing to the small pressure available and the friction in the mechanism. Moreover, when the gauge is allowed to remain under pressure for a period of several hours the reading tends to increase, due to elastic fatigue of the diaphragms. It will be observed that the glass front of the case has to

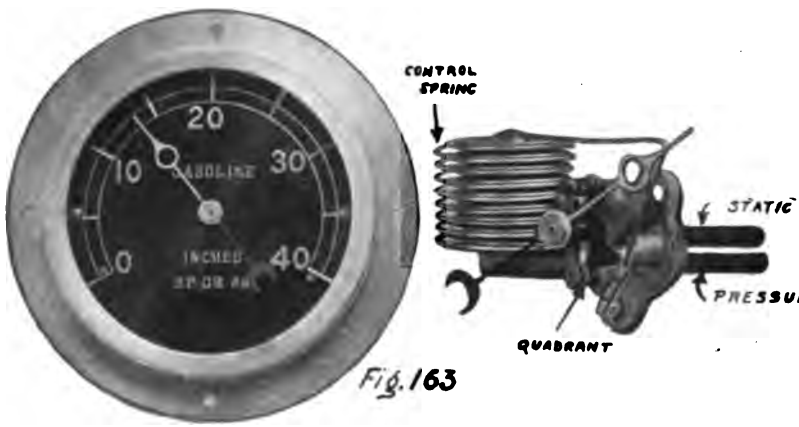



Fig. 163

be made pressure-tight when such gauges are used differentially. To avoid the necessity for this joint two diaphragm capsules connected differentially have been tried. It was found, however, that the sensitivity of the gauge was a function of the static pressure in the system, the variation being due to the initial distortion of the diaphragms.

### Griffiths' Liquid Depth Gauge

In 1917 the writer designed the gauge illustrated diagrammatically in Fig. 164 for use on aircraft, etc. It is so arranged that the indicator can be attached to the dash-board and connection made to the gauge tube fixed in the fuel tank by means of a pair of insulated wires.

This type of depth indicator is based on the principle that the heat loss from a wire is greater when it is immersed in a liquid than when in air.

In this liquid depth gauge a thin wire of platinum (or other metal) is

electrically heated to a temperature of about 20° C. above the surrounding air. The wire is insulated and suitably protected by a tube projecting to the full depth of the tank. The portion of the wire immersed in the liquid is cooled down to practically the same temperature as the liquid, whilst the part above the surface is at an excess temperature of say 20° C.

Since the resistance of metals, such as platinum, nickel, and copper vary with the temperature, the change being of the order of 0·4 per cent per degree centigrade, it follows that the average temperature, and hence the resistance of the wire, will depend upon its depth of immersion in the liquid. Now the most convenient method of measuring changes of electrical resistance is by means of the Wheatstone bridge, and in this gauge the wire forms one arm of the bridge, as shown in the diagram (Fig. 164). The influence of changes in the temperatures of the liquid and the atmosphere are completely eliminated by arranging alongside a similar wire, totally sealed off from the liquid and electrically connected in the other arm of the bridge.

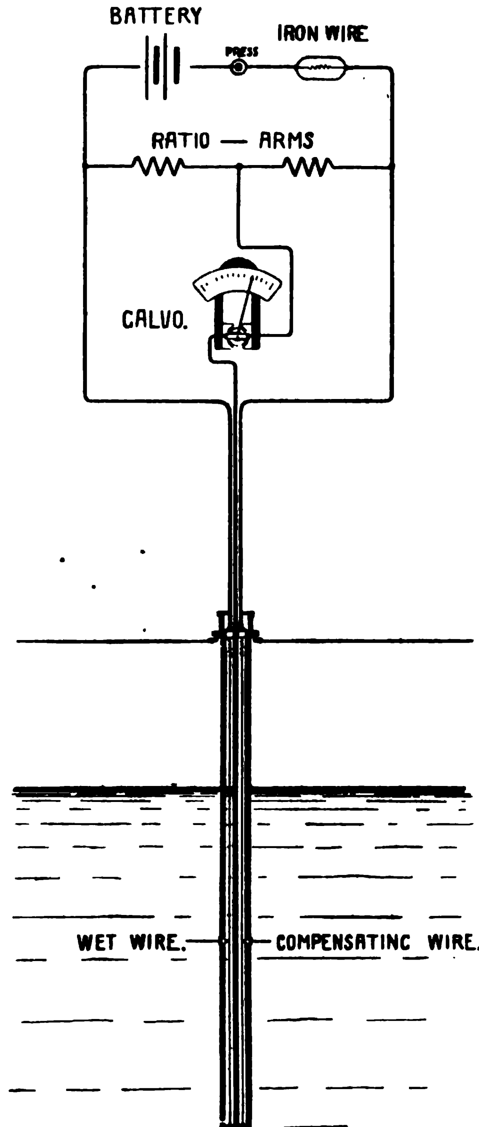


Fig. 164

The changes of resistance of the partially immersed wire, with variations of liquid level, is indicated by the deflection of the galvanometer pointer. The sensitivity of the method is such that a very small elevation of temperature of the wire suffices, and in practice a robust form of pivoted type of moving coil instrument is employed as indicator.

Since the sensitivity of any bridge arrangement is a function of the

current, it is necessary to keep this constant. The customary procedure is to have an adjustable series resistance in the battery circuit, and by means of a throw-over switch employ the same indicator as an ammeter when it is desired to adjust the battery current.

The necessity for this periodical adjustment is avoided in the present case by arranging an iron ballast resistance in series with the battery. The iron wires are sealed in a bulb similar to an electric lamp, with an atmosphere of hydrogen. Now the E.M.F. current of such resisters have the characteristic shown in Fig. 165.

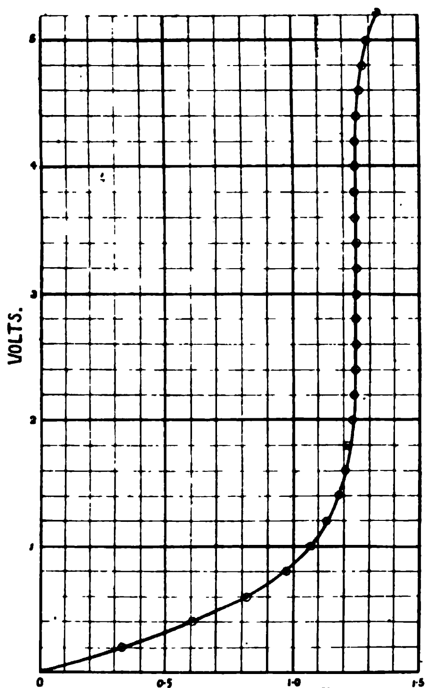


Fig. 165

A change of voltage from 2 to 4 volts at the ends of the iron wire has no appreciable effect on the current through the wire. This is due to the fact that pure iron has a very large temperature coefficient of resistance at a temperature of just visible red heat.

Hence the insertion of such a ballast resistance in the circuit absorbs the increase of voltage above a certain minimum, and so maintains a practically constant current in the bridge.[1]

Photographs of the indicator and of the tube containing the wires, which is projected into the tank, are shown in Figs. 166 and 167.

The ratio arms of manganin and ballast resistance are contained in the same case as the indicator.

## SECTION VI

### Volume Measurement of Solids

A novel application of the notch method of measuring volumes has been made by Mr. Lea, who has adopted it to the metering of the coal consumption of a boiler plant.

When the coal is supplied to a boiler by means of a mechanical stoker of the endless band or chain-grate type, the amount passing under the

[1] Calculation shows that a constant current gives equal sensitivity at all temperatures.

fire-door may be regarded as a stream whose width is constant, but whose depth and velocity are subject to variation from time to time.

If $W$ is the width of the stream in feet, $T$ the thickness or depth in feet of the stream, and $V$ the velocity in feet per hour,

Then cubic feet per hour $= WTV$.


Fig. 166

Fig. 167

Unfortunately, slack or small coal are not by any means perfectly homogeneous substances. Consequently it is not possible to convert the measured volume into weight units with accuracy.

If the coal were composed of spherical particles all of the same diameter and specific gravity, then the weight of unit volume would be a definite and calculable quantity. Moreover, this would be independent of the diameter, since it can be proved by calculation that the percentage of interstices is quite independent of the diameter of the individual spheres, provided that the size of the containing vessel is reasonably large as compared with the diameters of the spheres.

The packing in the ideal cases is illustrated by diagram (Fig. 168).

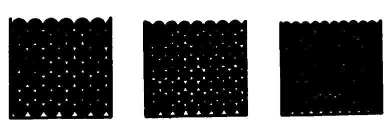


Fig. 168

Whilst small coal is not supplied in the form of perfect spheres, it has, however, been found by experiment that a load of " nuts " of uniform grade weighs approximately the same as a load of coal in " bean " or " pea " form.

Of course, if the coal is mixed—say lumps mixed with nut or slack—the weight per cubic foot will be proportionately higher on account of the finer particles filling up the interstices between the larger lumps, but such coal is rarely used with mechanical stokers.

When this method is employed in practice it is necessary to determine, from time to time, the weight of a cubic yard or so of the particular grade of coal used and employ this faetor for the conversion of the volume measurements to actual weights.

The specific gravity of coal is not a constant quantity but varies by as much as 20 per cent, and an idea of the influence of this on the weight of a cubic foot of solid and small coal may be obtained from consideration of the data in the table below :—

| Specific Gravity. | Weight of 1 solid cubic foot. | Weight of 1 cubic foot of small coal. |
|---|---|---|
| 1·20 | 75·00 lbs. | 40·50 lbs. |
| 1·25 | 78·12 „ | 42·18 „ |
| 1·30 | 81·25 „ | 43·87 „ |
| 1·35 | 84·37 „ | 45·56 „ |
| 1·40 | 87·50 „ | 47·25 „ |
| 1·45 | 90·62 „ | 48·93 „ |

*The Lea Coal Meter.*—The Lea coal meter is shown diagrammatically, (Fig. 169) and the recorder is identical with that employed in the case of the water meter.

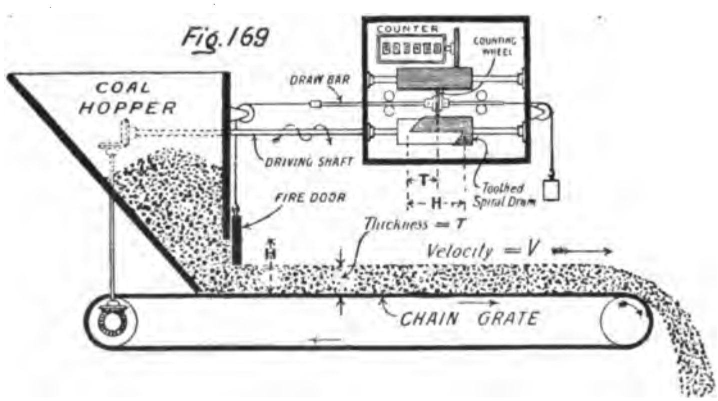


Fig. 169

The spirally toothed drum is geared to the grate so that its rate of rotation is proportional to the velocity of the stream, assuming there is no slip of the coal on the chain gate. A toothed counting wheel gearing with the spiral drum below and a counting box above is mounted upon

a rod or draw-bar directly connected with the fire-door, and as the fire-door is open or closed, the counting wheel is moved to and fro—laterally the spiral drum which revolves it, more or less, according to its lateral position.

It is thus obvious that for all variations in the thickness of the stream or the speed of the grate, the total number of revolutions of the counting wheel will be proportional to the total cubic feet of coal passed.

The makers guarantee an accuracy within 5 per cent by *volume*, under ordinary working conditions for the meter.

## REFERENCES

Hodgson. "The Commercial Metering of Air, Gas, and Steam." *Min. of Proc. Instit. Civil Eng.*, Vol. CCIV., p. 108. 1917.

——. "Recording Venturi Water Meter," *Engineering*, Feb. 22nd, 1907.

Davies and Jordan. "The Orifice as a means of Measuring Flow of Water through a Pipe," *Bulletin No.* 109 *of the University of Illinois*, Dec., 1918.

Gaskell. "Diaphragm Method of Measuring the Velocity of Fluid Flow in Pipes," *Min. Proc. Instit. Civil Eng.*, 1914.

Judd. "Experiments on Water Flow through Pipe Orifices," *Journ. Am. Soc. of M. E.*, Sept., 1916.

Coleman. "The Flow of Fluids in a Venturi Tube," *Trans. Am. Soc. M.E.*, Vol. XXVIII., p. 483. 1907.

Osborne Reynolds. "Dynamical Similarity," *Phil. Trans. Roy. Soc.*, p. 935. 1883.

Lord Rayleigh (the late). "Dynamical Similarity," *Phil. Mag.*, p. 321. 1899; *Advisory Committee for Aeronautics' Report*, p. 38. 1901–10.

Stanton and Pannell. "Similarity of Motion in Relation to the Surface Friction of Fluids," *Phil. Trans. A.*, Vol. CCXIV. 1913.

Stanton. "Mechanical Viscosity of Fluids," *Proc. Roy. Soc. A.*, Vol. LXXXV., p. 366. 1911.

Carl C. Thomas. "The Thomas Gas Meter," *Journ. of Ind. and Eng. Chem.*, Nov. 3rd, 1911.

——. "Some Recent Developments in Gas Measuring Apparatus," *Proc. Am. Gas Inst.*, p. 41. Oct., 1912.

——. "The Measurement of Gases," *Journ. Frank. Instit.*, p. 411. Nov., 1911.

Louis Vessot King. "The Linear Hot Wire Anemometer and its Applications in Technical Physics," *Journ. Frank. Instit.*, Jan., 1916; "On some Proposed Electrical Methods of Recording Gas Flow in Channel and Pipes, based on the Linear Hot Wire Anemometer."

Threlfall. "Flow of Air in Pipes," *Proc. Inst. Mech. Eng.*, p. 280. 1904.

D'Arcy. "Flow of Water," *Compt. Rendus de l'Academie des Sciences*, Vol. XXXVIII.

——. "Steam Meters," *Engineering*, Oct. 10th, 1919.

——. "Steam Meters," *Engineer*, p. 580. June 13th; *Journ. Frank. Instit.*, Vol. CLXXXII., p. 191. 1916.

Chattock. "Tilting Gauge," *Proc. Inst. Civil Eng.*, Dec., 1903; *Engineering*, Sept., 1913.

Töpler. "Differential Manometer," *Ann. d'Phys.*, Vol. LVI, p. 610. 1895.

Haanel and Blizard. "Meters for Producer Gas," *Summary of Report of Mines*, Branch of Dept. of Mines, Ottawa, p. 118. 1914.

Selvey. "The Measurement of Steam and Water in Power Stations," *Electrician*, June 27th, 1919, page 721.

——. "Water Meters," *Gas World*, Nov. 29th, 1919; *Gas Journal*, Nov. 25th, 1919; *The Iron and Coal Trades Review*, July 28th, 1916.

——. "Coal Meters," *Engineering*, Dec. 6th, 1918; *The Engineer*, March 14th, 1919.

Bailey, Ervin G. "Steam-Flow Measurement." [Paper describes a method of using $CO_2$ for calibrating purposes.] *Journ. Amer. Soc. Mech. Engineers*, Oct., 1916.

# CHAPTER V

## MEASUREMENT OF VELOCITY

### TACHOMETERS, SPEEDOMETERS AND MISCELLANEOUS SPEED-INDICATING DEVICES

ONE of the most important quantities of ordinary engineering practice is the rate of revolution of rotating parts. For instance, it is necessary to know the R.P.M. of machinery accurately in order to maintain the frequency of electrical alternating supply, to fix the most economical speed of machine tools, and for safeguarding machinery parts from excessive loads due to over-running. The angular velocity is an essential factor in the measurement of power output by dynamometer tests.

In addition to the above applications tachometers are often used to deduce the linear speed of motor vehicles and locomotives from the speed of rotation of their wheels. The simplest workshop method of estimating R.P.M. is by the use of a geared counter in conjunction with a watch. Such counters are made in various forms ; one familiar type is

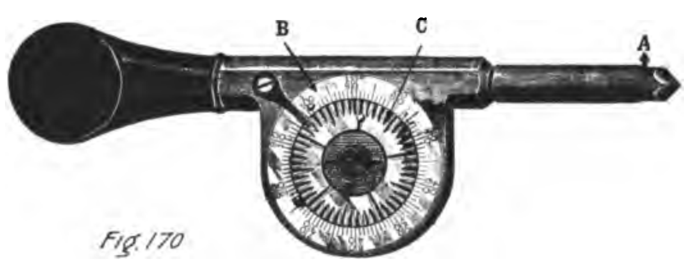



Fig. 170

*Revolution Counter*

shown in Fig. 170. The point $A$ with an appropriate adaptor is pressed firmly into contact with the centre of the rotating part or shaft and the number of turns of the disc $B$, which is geared 100 to 1, by worm and wheel, counted over a definite interval of time. The top disc $C$ is carried around one notch by friction with the wheel $B$ each time the spring finger is raised by the projection on the disc $B$, thus counting the hundreds of turns. If a sufficiently long interval of time is taken the value obtained

should be a fairly accurate average of the speed. In passing it might be remarked that care is necessary in the use of this type of instrument in the case of light machinery; the end thrust due to pressing the counter often materially reduces the speed.

A development of the counter principle in a convenient form is found in the Hasler instrument. In this device the watch and counter are combined and the operation of pressing one button winds the watch, automatically connects the counting train to the driving shaft for a definite period of seconds, and then disconnects it. The graduation on

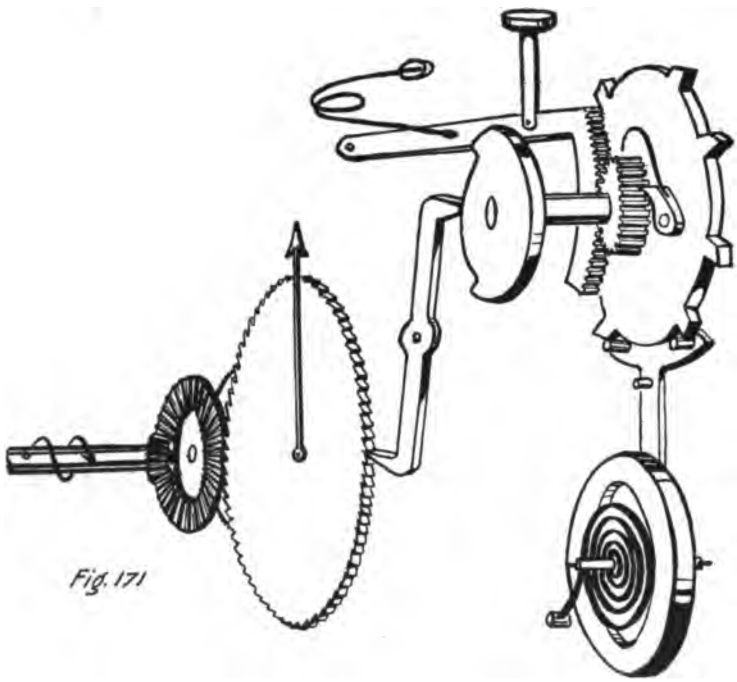


Fig. 171

the scale is arranged to read revolutions per minute directly. A diagrammatic sketch of the mechanism employed is shown in Fig. 171. The downward movement of the button depresses a rack against the pull of a small spring, when the button is released the spring drives the escapement wheel at a definite rate under the control of the balance wheel and lever. The shaft of the escapement wheel carries a cam, which after a rotation corresponding to one second releases the large ratchet wheel connected to the pointer. The wheel and pointer are then carried around by friction with the counter train for three seconds, after which interval the cam has rotated to a position in which the pawl is pressed up to arrest the motion of the ratchet wheel. The zeroising

button returns the pointer to zero after use in the same manner as a stop watch. A simple gearing in the counter train causes the pointer to rotate in a clock-wise direction for either hand rotation of the driving shaft. The instrument is very convenient and accurate in practice. It has the advantage of only needing a short interval of time for a determination of the speed.

Other combinations of watch and counter are in common use, but the two units are usually kept more distinct than the above-described instrument.

## SECTION I

For the continuous indication of speed the tachometers employed may be broadly classified into five groups, according to the principle upon which their action is based, which may be :—

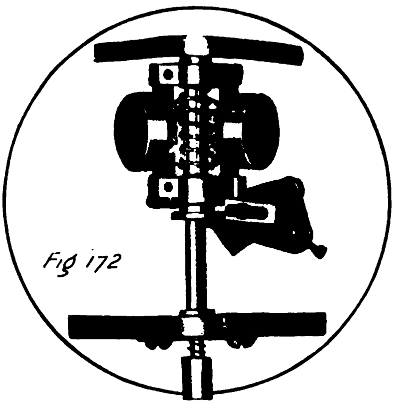
(*a*) Centrifugal force.
(*b*) Chronometric action.
(*c*) Magnetic drag.
(*d*) Electrical similar to dynamo.
(*e*) Viscous drag.

In the following description no differentiation is made between tachometers and speedometers, since the only point of variation is usually the addition of an oddometer or totaliser to the mechanism of the tachometer to convert it into a speedometer.

*Mechanical Centrifugal Instruments.*—Centrifugal tachometers depend upon the variation of the centrifugal force exerted by small masses rotating in a circle. The force tending to move each mass outward is proportional to the square of the angular velocity, multiplied by the radius of the circle on which it rotates. The masses are usually restrained by a spring, and the outward movement magnified by levers and gears.

The relation between displacement and speed varies for each particular design of instrument depending upon the configuration of the lever-system and type of spring control. The calibration cannot usually be predicted *à priori*. The chief endeavour of the designer is to make the lever arrangement such that the graduations on the scale are as nearly equidistant at all parts as possible. A typical example of a tachometer designed somewhat after the form of a Watts governor, is shown in Fig. 172. Three equal discs are arranged on short connecting levers at equal angles around the central spindle. These discs are thrown outward by the centrifugal force against the influence of the helical spring, and the

movement is transmitted through the collar to the geared quadrant which actuates the pointer wheel. The scale obtained is fairly uniform over an angular range of about three hundred degrees. The governor type of instrument is not much favoured owing to the comparatively




large number of joints in the levers which are apt to wear and cause back-lash. Generally the centrifugal masses take the form of a ring pendulum or a crossbar free to swing about an axis traverse to the rotating spindle.

A typical example of a ring pendulum mechanism is shown in Fig. 173, and is largely used for stationary machinery. This instrument was invented as far back as 1884 by Schaffer and Budenberg. The driving shaft carries a circular disc of metal $B$, the position of which when the shaft is at rest is rendered oblique to the shaft by means of a coil-spring contained in the barrel $C$. When the shaft rotates the centrifugal force tends to turn the ring, so that its plane is at right angles to the axis of the shaft. The movement of the ring is communicated by the rods $D$ to the sleeve $E$, and thence through the ball joint $F$ to the crank arm which actuates the quadrant and gear on the pointer spindle. The scale obtained is fairly uniform, but widens out somewhat at the middle of its range.

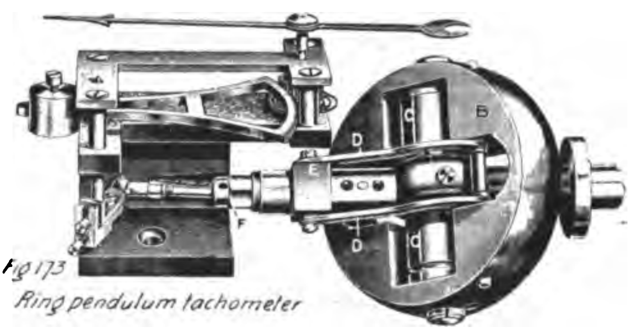



Fig 173
Ring pendulum tachometer

A lightly constructed modification of the above instrument is used on motor vehicles and aero engines. The ring is replaced by a crossbar, to which is fixed a pair of weights and a sliding muff, which gives a very simple form of construction, as shown in Fig. 174. The control spring is a flat coiled strip, and the motion is communicated by the connecting links to the sliding muff or collar. The groove in this collar engages with a

cranked pin on the gear quadrant, which in turn actuates the gear wheel on the pointer spindle. A small spring is fitted to the pointer spindle to take up back-lash. The pointer rotates through nearly one complete turn for the full range and in some cases, in order to give a still more open scale the graduation is arranged to start at, say, one quarter the full scale reading by putting an initial tension on the spring. Three-quarters of the scale is thus spread out to occupy the full length. Instruments of the type shown in Fig. 173 and Fig. 174 are not dynamically balanced at all speeds, and the couple at right angles to the driving spindle often causes the entire instrument to vibrate slightly if it is not rigidly mounted. Complete balance can be obtained by using two weighted bars disposed symmetrically on either side of the shaft, as shown in Fig. 175.

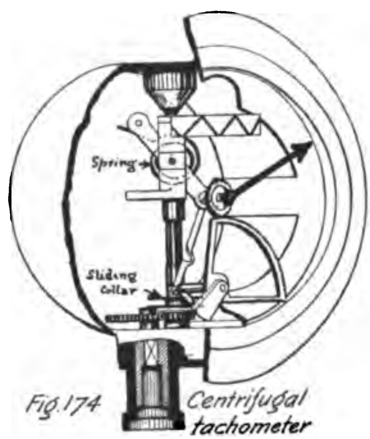



Fig. 174 Centrifugal tachometer

This centrifugal mechanism consists of four cylindrical weights $A$, mounted on two rectangular frames which are fixed cross-wise on pivots $B$ formed on the revolving spindle. The frames with the weights are

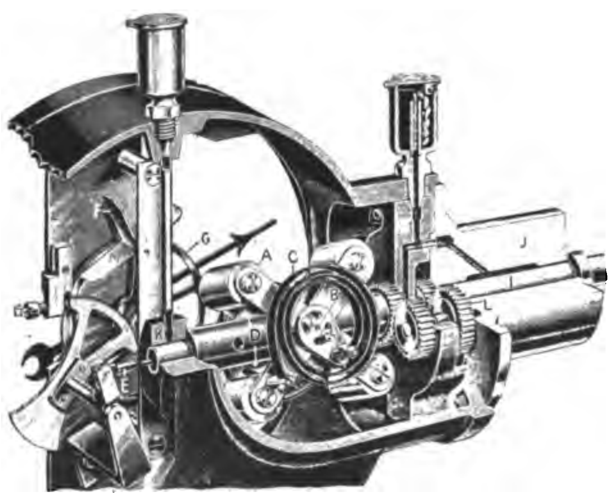



Fig. 175 _ Cross pendulum tachometer

free to rotate to a certain extent on these pivots, and the frames are connected by two steel spiral springs $C$. When the spindle revolves the centrifugal force tends to move the weights outwards, acting against the force of the springs, and this movement is communicated by two

links *D* to a sleeve inside the spindle. By means of a ball-joint and the connecting rod *E* the motion is transmitted to the quadrant of the indicating mechanism. A "damping" movement is provided in the mechanism to steady the pointer when subjected to sudden speed variations. This consists of a vane *F*, which is actuated from the pointer spindle by means of the gear wheel *G*. In the tachometer with internal gear, as shown in the above illustration, the main spindle is divided, a gear wheel on the end of the spindle by means of back-gear *L*, transmitting the drive to the inner spindle *D* on which the centrifugal mechanism is fixed. The sizes of the wheels of the gear are varied according to the ratio of drive that is required. The damping vane introduces considerable forces in the transmitting mechanism, and these parts need be substantially constructed unless some form of elastic buffer is inserted. The number of moving parts is, of course, greater than in the case of the ring pendulum.

All centrifugal instruments indicate the same for either direction of rotation. A few general considerations with regard to the design of centrifugal instruments might be mentioned here. The number of joints and levers should be kept as small as possible to avoid friction and slack due to wear. A hairspring should always be fitted to the pointer spindle to take up back lash as a little play is inevitable, particularly at the groove in the sliding collar. All the moving parts, including the gear quadrant, should be statically balanced to eliminate the effect of accelerations when the instrument is used on vehicles. The inertia of the moving parts should be as small as is consistent with sufficient power to actuate satisfactorily, especially if the instrument is to be used on machinery subject to sudden fluctuations of speed. Otherwise the driving shaft, if of the flexible type, is liable to be over-stressed by the inertia forces when the speed varies rapidly. The accuracy can be within $\pm 1$ per cent under ordinary conditions, although the author has found commercial instruments of the speedometer class to be in error often by as much as 6 per cent at full scale. The temperature coefficient is almost negligible for ordinary work.

*Chronometric Instruments.*—The name chronometric is generally applied to a class of instruments in which the number of revolutions made by the driving shaft is automatically and repeatedly counted for small equal intervals of time. The mechanism consists of a small clock escapement frictionally driven from the driving shaft, and some device operated by the clock which connects the driving shaft to the counting train for a definite time interval.

As a typical example, one of the least complicated of this class made by Van Sicklen will be described. This instrument counts the revolutions for repeated periods of one second, the pointer remaining steady at the reading for the average speed during the previous count. The mechanism is shown diagramatically in Fig. 176; the trains of wheels are of course omitted for clearness. The rotation of the driving shaft winds up by friction a watch spring which drives the escapement wheel. The spring barrel is fixed to the shaft which carries three cams. The escapement allows the cam shaft to make one thirty-second of a revolution suddenly every half-second. One of the cam followers moves the fine-toothed

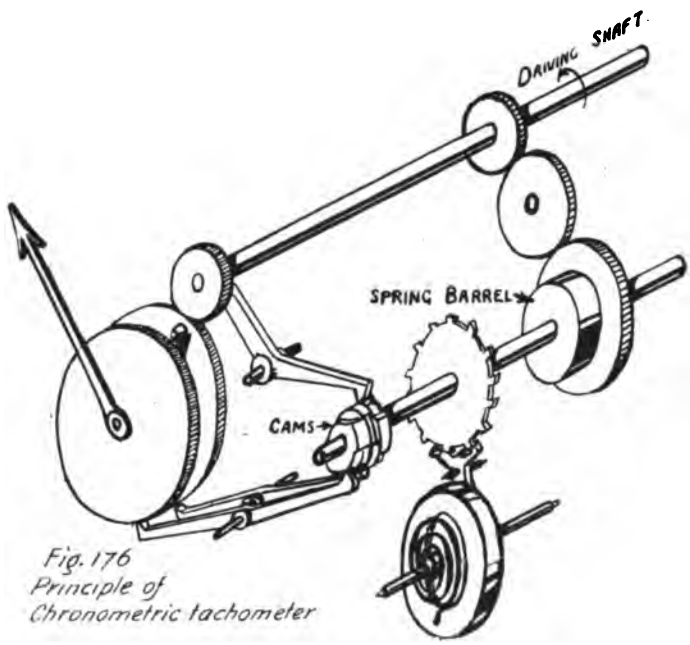



Fig. 176
Principle of
Chronometric tachometer

wheel on the driving shaft in or out of engagement with another wheel which is loose on the pointer spindle. The cam allows the wheels to engage for exactly one second. A similar fine-toothed wheel is fixed to the pointer, both of the wheels being controlled by hairsprings tending to return them to a zero stop. The other two cams actuate pawls working on the two wheels. The pawl on the loose wheel allows it to return to zero after each operation, so that the angle through which it is turned when thrown into gear with the driving shaft for one second is a measure of the R.P.M. of the latter. A projection on the loose wheel catches against a spring arm fixed to the pointer wheel and carries this wheel around with it. While the loose wheel is released to return to zero the

first wheel is held by the pawl. Should the speed vary the spring attached to the pointer wheel is pushed forward and the wheel takes up a new position when released by its pawl. When a decrease in speed occurs the wheel falls back until the spring reaches the projection. Thus the pointer does not return to zero after every count, but remains indicating the speed for the previous second.

Other instruments of this class have more elaborate mechanism; for example, the "Tell" instrument has three vertical parallel shafts. The first carries three sets of cams, and its speed of rotation is governed and kept constant by the escapement. These cams, of which there are six, act through six levers on to three double crown wheels mounted loosely on the second shaft. Three levers have ratchet ends which engage with the teeth on one side of the crown wheels, and lock them, whilst the other levers actually lift the crown wheels and bring them alternately in and out of mesh with pawls which are carried round by the second shaft, which is driven from the main driving spindle of the indicator, the speed of which is required to be known. Each double crown wheel drives one of three fairly large diameter wheels on which a pin projects which carries forward a bar fixed on two arms and rotating on the same axis. The second and third double crown wheels act in a similar way at equal intervals of time, in such a way that the preceding wheel is not "unlocked" until the next one has been urged forward and locked in the position to which it has been wound in the interval during which it is driven from the main spindle.

The action is as follows: The cams throw a double crown wheel into mesh with the driving spindle for a definite period of time, and at the instant of being thrown out of mesh they are locked in position. During this time the bar has been carried forward against a spring which tends to return it to a zero position. Before the first wheel is unlocked a second has gone through the same cycle and subsequently maintains the position of the bar unless the speed has altered in the interval, in which case it pushes it farther forward for an increasing speed and lets it back if the speed has decreased. The large wheels gearing with the double crown wheels are also returned to a zero position by means of a spring. The movement of the bar is recorded by the pointer through a special form of rack and pinion gearing. There are, of course, several other well-known chronometric tachometers, such as the Jaeger and Isochronous, but they do not differ sufficiently from the foregoing to need special description here.

Chronometric instruments have a perfectly uniform scale over the

entire range of speed indicated, and, moreover, the scale is fixed by the dimensions of cams and wheels and can only be changed by the wearing down of the cams or changing the wheels in the counting train. The accuracy of the best class of commercial instrument is within $\pm\frac{1}{2}$ per cent of full scale reading. The attainable accuracy is, however, governed by the size of the teeth on the wheels, since in some instruments the width of a tooth may be equal to several R.P.M. divisions on the scale. The temperature coefficient is practically that of the time element in the mechanism and negligibly small. If a flexible driving shaft is used this should be arranged to run very steadily, otherwise a movement of the pointer occurs up and down in small jerks, rendering a true average difficult of estimation.

*Centrifugal Fluid Tachometers.*—Tachometers depending upon the centrifugal forces brought into play by the whirling of fluids are characterised by the simplicity of their construction and by the fact that the calibration can usually be calculated from the dimensions of the instrument without reference to a standard for comparison, which, of course, is a considerable advantage. The most elementary example of the fluid type is the rotating cup used as a rough indicator on centrifugal cream-separators, etc. When a body of liquid is rotated in an open vessel the free surface of the liquid takes the form of a paraboloid with its apex on the axis of rotation and pointing downwards. Fig. 177 is a sketch of the form of the liquid surface.

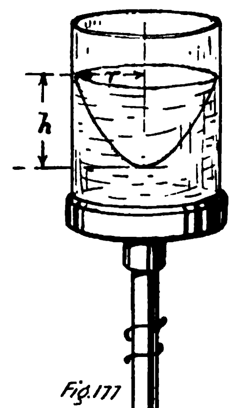


Fig. 177
Cup tachometer

The depression can be shown mathematically to be equal to

$$h=\frac{w^2r^2}{2g} \text{ or } h=\frac{\pi^2n^2r^2}{30g}$$

where $r$=radius of free surface
$n$=speed in revolutions per minute
$g$=acceleration due to gravity.

The value of $h$ therefore depends on the square of the speed and the device is thus most suitable for high speeds. Since the depression is also proportional to the square of the radius of the free surface, it is evident that if the shape of the cup is other than parallel the calibration can be made to vary from the square law, and shaped cups are sometimes used in practice.

An interesting case of whirling liquids is that in which the liquid is contained in a closed cylinder, and the edge of the parabola touches the

top of the vessel after a certain speed, as shown in Fig. 178. It can be proved theoretically that the depth $h_1$ of the parabola after this critical value becomes a linear function of the speed.

$$\text{That is } h_1 = wr\sqrt{\frac{h}{2g}}$$
$$= 2\pi nr\sqrt{\frac{h}{2g}}$$

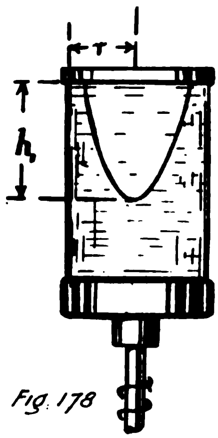



Fig. 178
Closed cup tachometer

where $h_1$ is the depth from the top of vessel. $h$ is the depth of paraboloid just as it touches the top.

$r$ is radius of cylinder.

The calibration will therefore vary as the square of the speed up to a certain value determined by the point where the liquid edge just touches the top, and above this value of the speed the depth of the apex will vary directly as the speed. This particular form of cup is the one generally used in tachometers.

*Centrifugal Pump and Pressure Gauge Instrument.*—Tachometers which utilize the dynamic head or suction created by an elementary centrifugal pump are a well-known class of speed measuring instruments. This principle was first used by Stroudley in 1879. One form of self-contained tachometer is shown in Fig. 179, and in section in Fig. 180. A small impeller with radial vanes rotates in a chamber containing liquid, and the head due to centrifugal force on the rotating fluid is transmitted to the column above the body of the instrument. A small reservoir surrounds the bottom of the tube to indicate the zero or datum line of pressure, and it is a very important point that this should not change due to leakage, etc., as any variations in level affect the height of the pressure column by an equal amount.

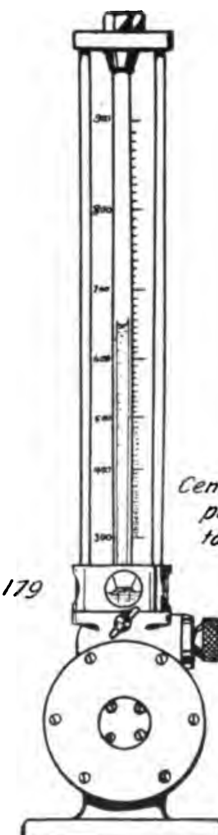


Fig. 179
Centrifugal pump tachometer

The calibration of the scale is very nearly proportional to the square of the speed, and

the instrument is well suited for fairly constant speed machinery, since the indication can be arranged to occur at the upper or open part of the scale by the use of the appropriate gear ratio. The square law scale is not a convenient one for a standardising instrument, since the divisions are very close at one end of the scale and it is difficult to read the meniscus. The accuracy of fluid types of tachometers depends very largely on the construction and the conditions under which they are used.

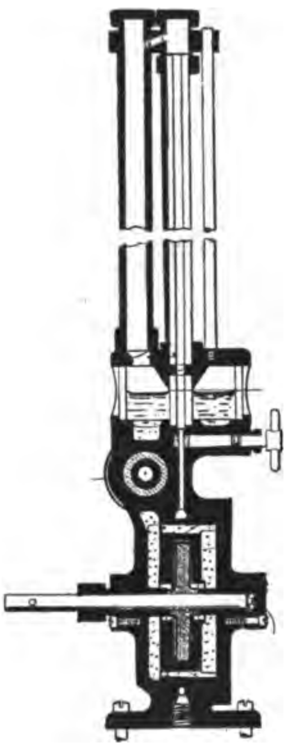


*Fig. 180.—Section of Centrifugal pump tachometer*

All the above instruments are of course independent of the density, as this factor enters directly into the dynamic head produced by the pump and the hydraulic head of the measuring column. Also for the same reason they have a very small temperature coefficient, provided all the liquid is at a uniform temperature. Which condition demands that self-heating in the pump should be negligible.

*Aerodynamic Tachometers.*—Instruments depending upon the centrifugal force exerted by an air column when rotated, have found some slight application. Their chief merit lies in their simplicity.

The usual arrangement is shown in Fig. 181. The tube $A$ rotates about a vertical axis, and the centrifugal force on the particles of air contained in the tube creates a radial pressure gradient. The pressure at the open end of the tube being equal to that of the atmosphere, a suction is set up at the centre, and this suction is measured by a U-tube, or a sensitive vacuum gauge fixed at any convenient point. The joint between the rotating tube and the stationary tube is effected by a simple mercury seal. The suction obtained varies as the square of the speed and is, of course, very small even when the instrument runs at a high speed.

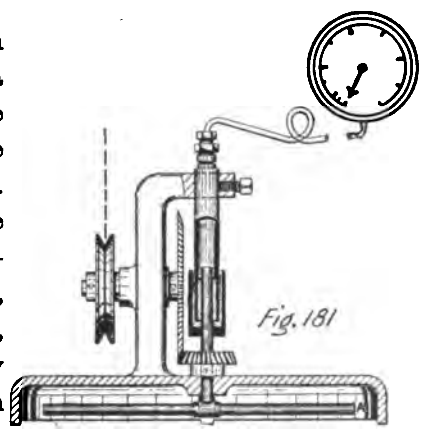


Fig. 181

One of the disadvantages of this type of instrument is the influence of the variability in the atmospheric density due to changes in the barometer and the temperature. An error amounting to several per cent is possible from day to day due to these causes.

Another aerodynamic instrument which does not, however, depend upon centrifugal force, might be mentioned in passing, and that is the Air-Vane type. The principle of this device is the use of two small air vanes mounted in close proximity, one rotated by the driving shaft and the other pivoted and free to rotate under the control of a spring. The torque on the pivoted vane depends approximately upon the square of speed of the driven vane and directly upon the density of the surrounding medium (air). The spring is so arranged that the controlling force increases with the deflection to counteract the increased torque, and this gives a fairly uniform scale. The disadvantage of variable density, already mentioned, limits the accuracy obtainable. Moreover, the rotation of the vane itself tends to heat up the air inside the case which results in a change of density. This inaccuracy could be eliminated by hermetically sealing the case, but the expedient would give rise to serious practical difficulties in the construction.

*Magnetic Tachometer.*—It is a well-known fact that if a magnet is rotated near a sheet of electrically conducting material, the sheet will experience a couple about the axis of rotation of the magnet due to the eddy currents induced in it by the motion of the magnet. This principle has been used in a damping device in electrical instruments. Tachometers designed on this simple principle have found extensive application. The two best known instruments of the class are the "Warner" and the "Stewart."

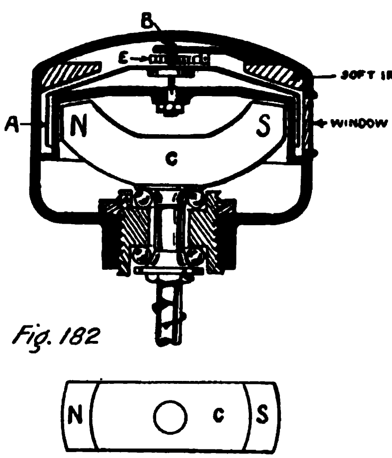


Fig. 182

The Warner instrument (Fig. 182) has a metal drum $A$ mounted on the axis $B$, so that its rim cuts the field due to the magnet $C$. The magnet is rotated by a shaft connected to the machine, whose R.P.M. is being measured. The eddy currents induced in the drum drag it around against the action of the spring $E$. The edge of the drum is graduated and viewed through a small window at the side. The divisions are equidistant at all points

of the scale. The adjustment for calibrating the instrument is made by simply screwing the bearing in or out to decrease or increase the air-gap in the magnetic path and thus vary the deflection.

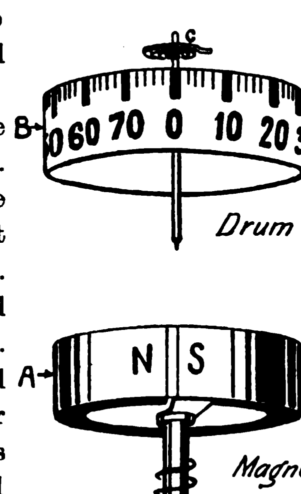



Fig. 183

The Stewart instrument is simpler, the magnet being circular, as shown in $A$ (Fig. 183). The eddy current disc, as in the Warner, is made in the form of a drum $B$, fitting over the magnet with one long pivot $C$ in the axis of the magnet. In order to reduce friction no bearing is fitted at the top, where the control spring $C$ is fastened. The graduations in the simplest form are printed directly on the edge of the drum, but a pointer may be fitted if desired. A simple method is employed to set the calibration. The magnet $A$ is provided with a small soft iron plate, fitting tightly on the axis, and by rotating this plate by a very small amount relative to the magnet, with which it turns, more or less of the magnetic field can be short-circuited. The magnetic field in which the drum moves can therefore be changed and the calibration set, or corrected at any time, provided the magnet is not too weak.

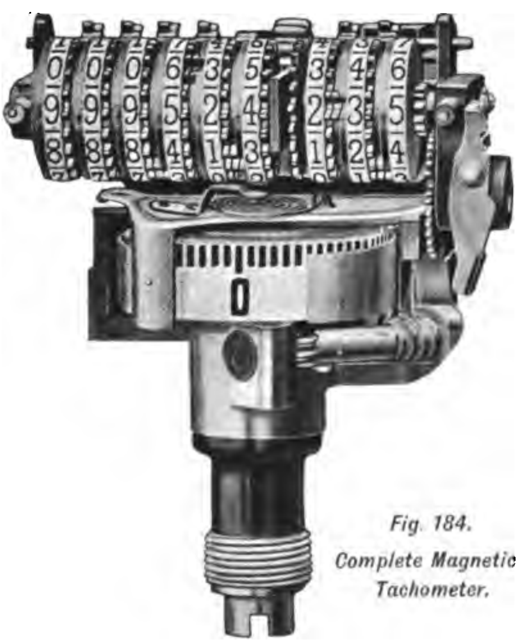


Fig. 184.
Complete Magnetic Tachometer.

A complete instrument with the mileage counter suitable for motor-car work as a speedometer, is shown in Fig. 184. The temperature coefficient of this type of tachometer is usually very large, being of this order of ½ per cent per degree centigrade. To obtain as great torque as possible on the disc for a given speed the magnetic field should be strong and the disc of low electrical resistance. The first factor is limited by the size of the magnet, which must not be cumbersome or possess a large moment of inertia. The second factor, low electrical resistance, demands

the use of a pure metal, such as silver, copper, or aluminium. Aluminium is the one in general use on account of its low density. These metals have temperature coefficients of resistance of the order of 0·4 per cent per degree, and to completely eliminate this factor would necessitate the use of some alloy, such as manganin, which has the attendant disadvantage of high specific resistance. If a drum of this alloy were used the torque would be reduced in the inverse ratio of the electrical resistance, i.e. 1 to 30 approximately. It would not, of course, be difficult to devise automatic compensation for the temperature coefficient, but in commercial practice very little attention is paid to the point, cheapness of construction being a vital consideration. Some models of the Warner instrument

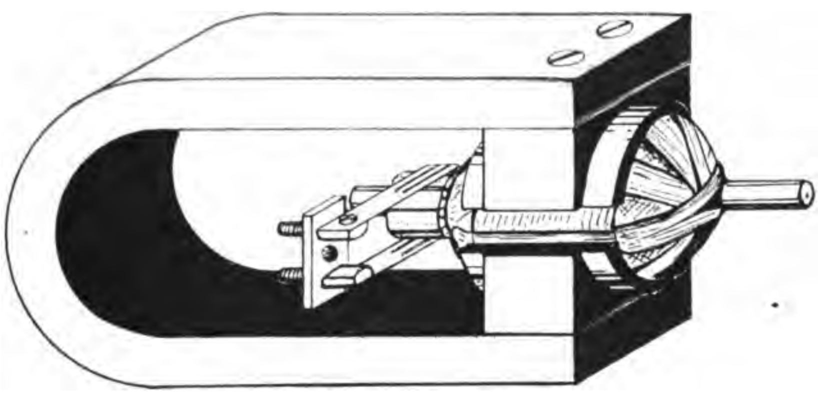


Fig. 185_ Generator of electrical tachometer

have a bimetallic strip compensator, and this is very effective, but there is a tendency to over compensate in practice.

*Electrical Tachometers, Magneto Generator Instrument.*—This type of tachometer is widely used under conditions where the indicator has to be placed at a considerable distance from the machine whose speed is required, as, for example, on board ship. The essential parts of the device are a small generator generating continuous or alternating current; this generally takes the form of a permanent magnet dynamo and a suitable voltmeter with a scale graduated in R.P.M. A generator of the continuous current type is shown in Fig. 185. The armature may have from six to eighteen slots, according to circumstances, and it is desirable that the maximum number of turns should be wound to obtain a high voltage. This armature rotates in a tunnel in the soft iron shoes fitted to a permanent magnet or alternately in a tunnel ground in the ends of the magnet itself. The clearances between the rotating parts should be made very

small, as this is advantageous in two ways. It helps to maintain the strength of the magnet constant, and also gives a stronger magnetic field. This small clearance is by no means as universal as it should be. The commutator and brushes both require careful design and skilled workmanship. Carbon brushes need a considerable pressure, and are liable to chatter under vibration. They are, moreover, susceptible to any readjustment, and must be run in before the calibration becomes consistent.

The modern tendency is towards brushes made from narrow strips or fingers, both brushes and commutator being made of silver or gold to avoid oxidation. The current taken from these generators is so small that armature reaction does not enter into consideration, and the voltage generated is almost exactly a linear function of the speed. The indicator is a standard electrical instrument of moving coil pattern, as shown in Fig. 186. This instrument is connected by a pair of insulated wires to the terminals of the generator, and the distance between the two units is quite immaterial, provided the electrical resistance of these leads does not become comparable with that of the instrument. The current in the circuit is usually not more than about one-hundredth of an ampere at full scale, and as the magneto generates at least five volts per thousand revolutions, a large swamp resistance is employed in the circuit.

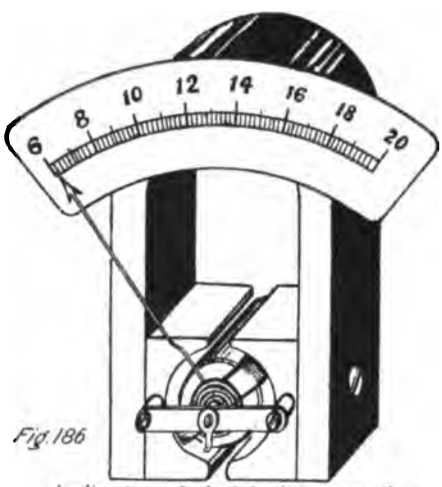



Fig. 186

Indicator of electrical tachometer

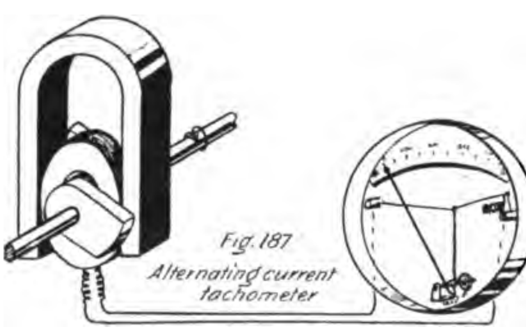
The object of generating a comparatively high voltage and then using a high resistance in the circuit is twofold. In the first place it renders the variations in the resistance of the connecting wires unimportant, and, secondly, it enables the effects of changes in temperature to be rendered small. The temperature coefficient is the most serious difficulty in connection with the design of electrical tachometers. Temperature changes affect (*a*) the magnetic strength of the magnets in both instrument and generator ; (*b*) the strength of the control spring in the instrument ; and (*c*) the resistance of the windings of both indicator and generator. The temperature coefficients of the magnet and the spring in the indicator may, to some extent, counteract one another ; but the tempera-

ture effect on the magnet of the generator is still uncompensated for.

The resistance of the copper winding can be made small in value in comparison with total resistance. This artifice, however, only affords a partial solution of the difficulty, and it would be preferable to eliminate copper entirely from the windings of both the indicator coil and the generator armature and use an alloy of negligible temperature coefficient such as manganin. The writer has tried this and found it successful, the only practical difficulty being the stiffness of the manganin when winding the moving coil former. It would of course be possible to use very fine wire under these conditions, since the " swamp " resistance is not now required and need only be retained for the purposes of adjustment to secure correct range and interchangeability.

The temperature coefficient of a well-designed electric speed measuring set can be made of less than 0·1 per cent per degree C., but the average instrument is found to have a temperature coefficient of more than twice this amount. It is advisable to shield the instruments, both generator and indicator, in soft iron cases to eliminate the effect of stray fields and the proximity of magnetic material.

Alternating current tachometers were at one time used to a considerable extent on motor vehicles and were very simple in construction. The generator was of the simple inductor type with a stationary winding, and without either brushes or slip rings. The indicator was a miniature hot wire instrument, the indication depending on the expansion of the wire due to the heating effect of the electric current. A sketch of the complete instrument is shown in Fig. 187. The arrangement was cheap to construct and compact in form, but no attempt was made to attain great accuracy or to reduce the temperature coefficient.




*Squirrel Cage Speed Indicator*.—An interesting instrument, which depends upon the angular position of the resultant of two magnetic fields in the interior of a squirrel cage winding, has been invented by Mr. E. B. Brown, of Melbourne. The instrument consists of a cylindrical soft iron armature core, which can be rotated on its axis between pole-pieces attached to a permanent magnet. This armature is provided with slots

or tunnels carrying a number of insulated conductors short-circuited by rings at both ends of the armature in a manner similar to the well-known squirrel cage winding used in A.C. motors. At one end of the armature the squirrel-cage projects considerably beyond the armature core, as shown in Fig. 188, in which $A$ is the armature core (which may be laminated), $C$ are the conductors which may be any number from three up-

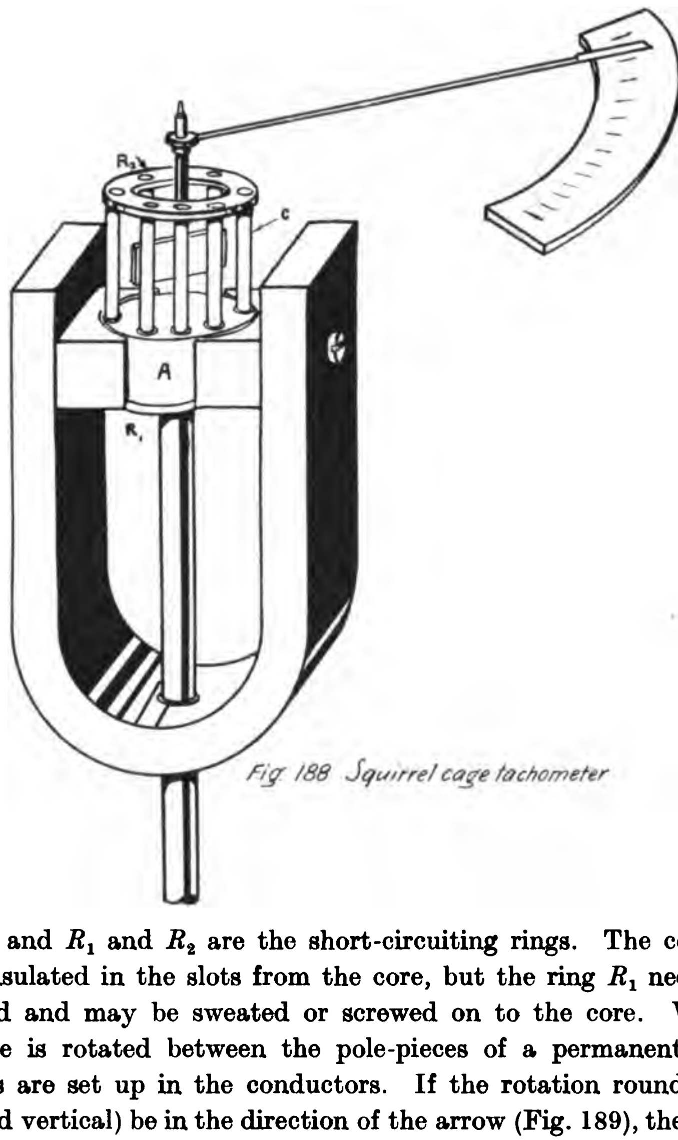



Fig. 188 Squirrel cage tachometer

wards; and $R_1$ and $R_2$ are the short-circuiting rings. The conductors $C$ are insulated in the slots from the core, but the ring $R_1$ need not be insulated and may be sweated or screwed on to the core. When the armature is rotated between the pole-pieces of a permanent magnet, E.M.F.'s are set up in the conductors. If the rotation round the axis (assumed vertical) be in the direction of the arrow (Fig. 189), the E.M.F.'s will be upwards on the left-hand side of the armature, and downwards on the right-hand side. There will consequently be a belt of currents

flowing up one side of the armature and down the other. The direction of the currents in the conductors is indicated in Fig. 189, and also the forward displacement of the line of zero current, which results from the self-induction of the armature winding.

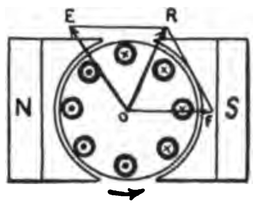


Fig. 189

As is well known, the currents flowing in the conductors of the projecting squirrel cage winding produce a cross magnetic field in the space within it, indicated by $O\,E$ in Fig. 189. In this plane there is already a magnetic field due to leakage from the magnet poles, which is called "the initial field" and indicated by $O\,F$. The field $O\,E$, due to rotation of the armature, is called "the deflecting field" and combines with $O\,F$, the "initial field" to produce $O\,R$, "the resultant field." The direction of $O\,R$, "the resultant field," depends on the speed of rotation of the armature, and it is only necessary to add a small pivoted vane of soft iron attached to a pointer and some form of damping mechanism, to make the apparatus a practical speed indicator. The soft iron is enclosed in a fixed tube to prevent the action of air currents (this is omitted from the diagram for clearness), and is attached to a vertical pivoted axis, which also carries an air-damping vane and a pointer moving over a graduated scale.

As is usual in instruments of this type, the moving element is balanced about its axis by balance weights (not shown in Fig. 188), so that the instrument can be used in an inclined position. It may be remarked that no control spring is necessary, because the plate of soft iron takes up the direction of the resultant field, and also that moderate variations in the moment of the magnet will not affect the indications of the instrument, since they affect both initial and deflecting fields in the same ratio, and thus the direction of the resultant is unchanged.

The calibration curve of one of the instruments used in Melbourne University is given in Fig. 190, which shows the form of scale obtained. It is stated that the instrument can be used close to dynamos and motors when provided with a cast-iron case to diminish stray field errors. The upper ring of the rotor is made of an alloy with a low temperature coefficient of electrical resistance, in order to diminish errors due to change of rotor resistance with temperature. Under the conditions in which it is used the instrument is claimed to give readings which may be relied on within $\pm\frac{1}{2}$ per cent.

*Viscosity Instruments.*—Tachometers making use of the variations in the viscous drag on a solid immersed in a whirling fluid have been

developed in a variety of forms, such as shown in Fig. 191. In this type, which is used on aircraft, the arrangement consists essentially of a

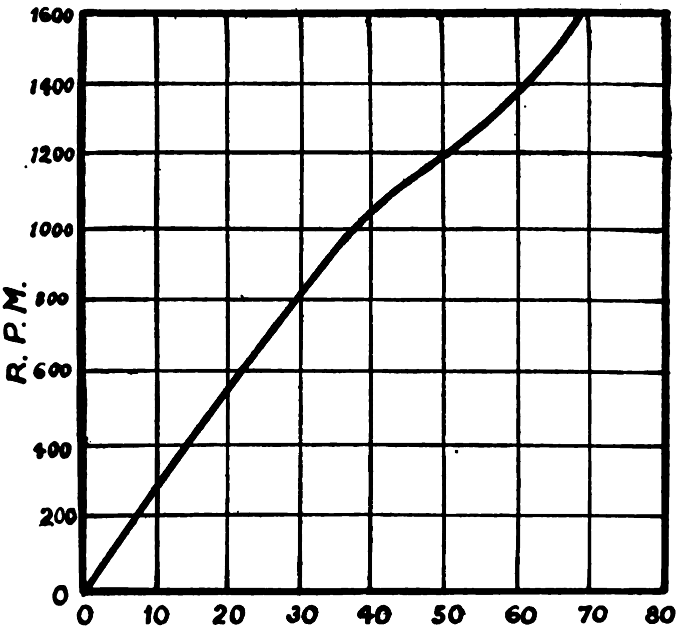



Fig. 190

perforated circular disc fixed to the driving shaft and rotating close to a small cross-arm fixed to the pointer spindle, as shown in the sketch (Fig. 192). The disc and arm are contained in a cavity full of mercury.

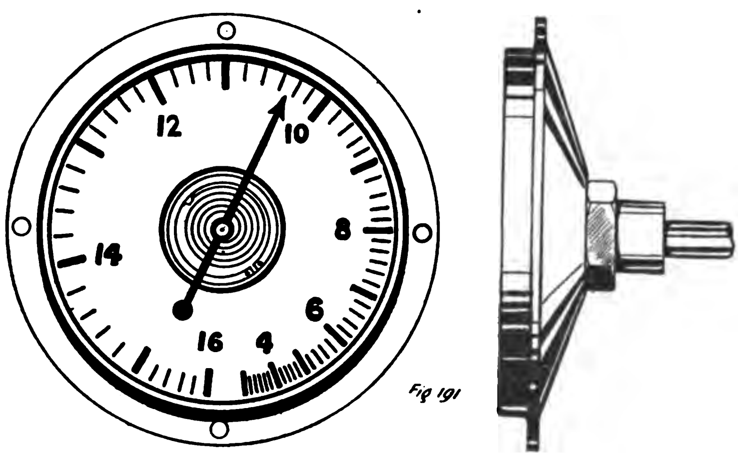



Fig 191

The mercury, being carried around by the disc, tends to drag the cross-arm with it against the pull of the spiral spring. The torque exerted upon the arm depends approximately upon the square of the speed and the scale

opens out, as shown in Fig. 191, in the middle, but closes in suddenly near the top, due presumably to slip between the mercury and the plate. The device is very simple and compact, the mercury chamber being only about one inch in diameter in the instrument sketched. The instrument is fairly reliable; its chief disadvantage lies in the fact that the spindle

*Mercury viscosity tachometer*

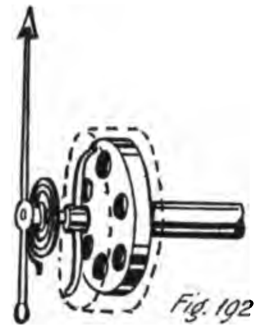
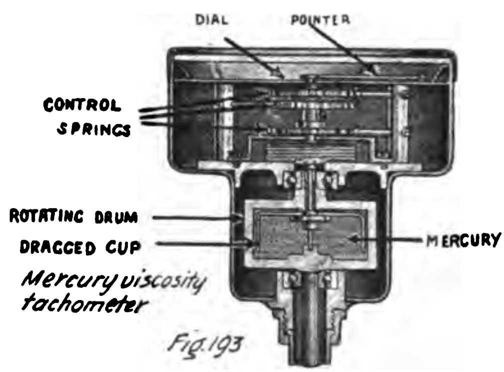


*Fig. 192*

of the pointer has to pass through a hole and be made mercury-tight. The friction here must necessarily be more than if the spindle were pivoted. The temperature coefficient of viscosity is small. In the case of a well-made instrument the temperature coefficient was found to be 0·03 per cent per degree C., and this includes the temperature coefficient of the control spring.

A slightly different type of mercury viscosity instrument to the above has been made for use on motor vehicles. This particular instrument




*Mercury viscosity tachometer*

*Fig. 193*

employs a rotating cup containing mercury immersed in which is a small drum, as shown in Fig. 193. The drum is fixed to the pointer spindle and controlled by spiral springs. This spring control is of a novel type in so much that an attempt has been made to equalise the spacing of the graduation by the use of three control springs of different strengths; these springs are not rigidly fixed to the spindle carrying the pointer,

but come into action on contact with a stop on the spindle at a definite angular position. The controlling force is thus due to one spring only at the beginning of the scale and to the sum of three springs at the top end when the torque due to viscosity is greatest.

*Viscosity of Air Tachometers.*—The advantages of using air as the viscous medium in a tachometer are obviously considerable, since the spindle need not pass through a liquid-tight joint. But, on the other hand, the forces obtained are very much smaller than those available with liquids, such as mercury, and consequently the workmanship must be very good to produce a satisfactory instrument.

A speedometer has been introduced recently by the Waltham Watch Co., in which the viscous drag between concentric cups is utilized. The device consists of two brass cups fixed to the driving shaft, telescoping into which are two inverted aluminium cups pivoted and controlled by a spiral spring. The arrangement is shown in sketch (Fig. 194). The air-gap between the adjacent walls of the rotating and stationary cups is only half a millimetre. The aluminium cups are very light, the wall being only 0·08 of a millimetre in thickness. The spindle is mounted in jewel bearings: the method of mounting is shown in sketch Fig. 195.

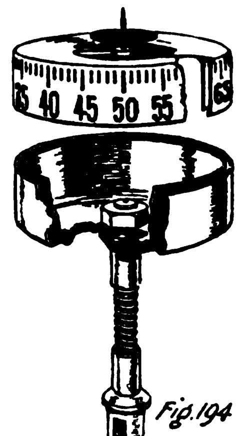
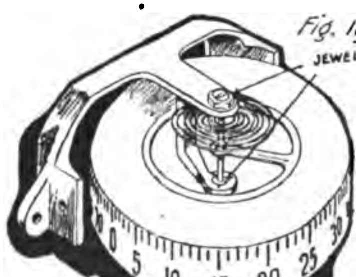



Fig. 194
Air viscosity tachometer

The scale is marked on the outer surface of the aluminium cups and the general appearance of instrument (Fig. 196), resembles a magnetic eddy current type of instrument. The graduation of the scale is uniform,

Fig. 195




Drum of air viscosity tachometer

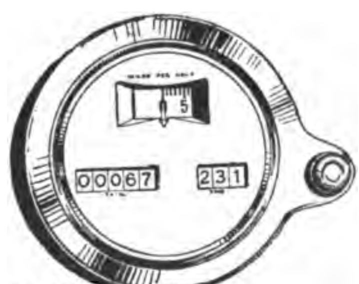



Fig. 196

the deflection being proportional to the speed. It can be shown by experiment that the general law of viscosity for this type of arrangement is of the form torque $\propto \frac{Vs}{d}$

Where $V$=relative linear speed of the surfaces,
$S$=area of surface.
and $d$=distance between them.

This law holds up to a critical velocity, after which the index of $V$ increases to approximately the second power. The fluid instruments already considered work over a range of velocities above this critical velocity, since its value is very low for liquids. The air viscosity instrument, however, is arranged to run at low speed (about 1000 R.P.M. at full scale), and the greater torque incidental to high speeds of rotation are sacrificed to retain the linear calibration. An arrangement is provided to cause frictional damping when fluctuating speeds are measured. This consists of a small disc at the top of the drum spindle, on the surface of which bears a jewel on the end of a spring, so that by varying the pressure more or less friction is introduced; such damping is of course obtained at the expense of sensitivity. The damping of the motion of the moving systems of instruments is considered in detail on page 201.

*Resonance Tachometers.*—Resonance instruments of the reed type are often used in electric generating stations where machinery runs at a fairly constant predetermined speed. It is a well-known fact that if a flexible bar or reed is rigidly connected to a support which is vibrating or subject to impulses of definite frequency, the bar will vibrate in resonance with a considerably greater amplitude than that of the support if the period of the impressed oscillation is equal to, or is a definite multiple of, the natural period of vibration of the bar. Generally a piece of rotating machinery possesses a slight out of balance effect which sets the entire machine and bed-plate in vibration, and usually the oscillations set have the same period as the speed of rotation. A reed of the appropriate period will therefore resonate if fixed to any part of the machine. In practice an instrument is made up of a series of reeds of uniformly decreasing period and mounted in a case, as shown in Fig. 197. The reeds usually take the form of steel strips of varying lengths loaded at the end (Fig. 198), the period being initially adjusted by filing down the weight. The weight of the white paint on the tips has an appreciable effect on the natural period of the reed and consequently must not be liable to flake off or absorb moisture.

If the number of reeds cover a wide range of speed, then more than one reed will respond to a given vibration, since the reeds whose periods are multiples of the particular frequency will be set oscillating. The primary frequency can, however, be recognized as that of the reed having greatest amplitude. The case of the instrument is usually mounted

direct on the machine. The amplitude of the reed is normally as shown in Fig. 199, but if found to be insufficient for easy observation, use can be made of a springy support, such as a steel arm, for the case; on

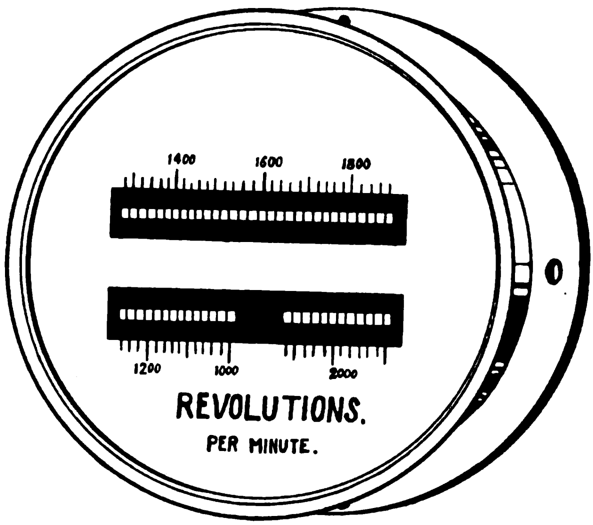



Fig. 197 – Resonance tachometer

the other hand, if the amplitude is too great, then a pad of soft material, such as felt, is interposed between the case and its support.

This type of tachometer is sometimes used as a transmitting instrument by the addition of an electro-magnet to excite the reeds and a make and break contact on the rotating shaft; the instrument then being

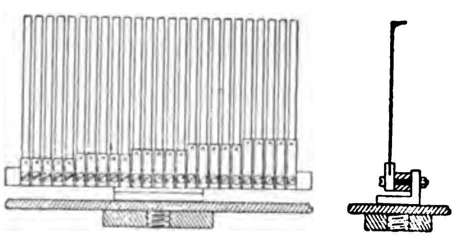


Fig. 198 – Reed system

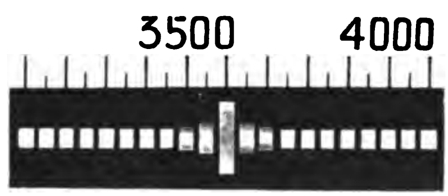



Fig. 199 – Appearance of vibrating reeds

identical with the electrical frequency meter used on alternating current circuits.

*Miscellaneous Tachometers—Boyer Recorder.*—The indication of this tachometer depends upon the pressure generated by a pump delivering oil through a variable orifice. The instrument is designed primarily as a recorder for railway work. The pump is of the well-known type, employing two meshed cog-wheels driven in opposite directions from the driving

shaft. This forces oil into a cylinder, displacing a piston against the pull of a spring; the oil escapes through an adjustable slot in the side of the cylinder. Since the quantity of oil delivered by the pump varies directly as the speed, the piston must move upwards to increase the size of the slot and the pressure to a sufficient extent to permit the increased quantity to pass. The piston rod carries a pen recording on a drum, and also transmits the indications to a dial gauge by means of a chain and pulley arrangement similar in form to the simple string type of level gauge described on page 143. The instrument's great merit is its robustness, which fits it for the somewhat trying conditions prevailing on locomotives. The temperature coefficient cannot be made small, since the discharge of this type of pump, and the flow through the orifice, will be influenced by changes in viscosity, etc.

*Inertia Wheel Tachometer.*—A novel principle has been utilized by

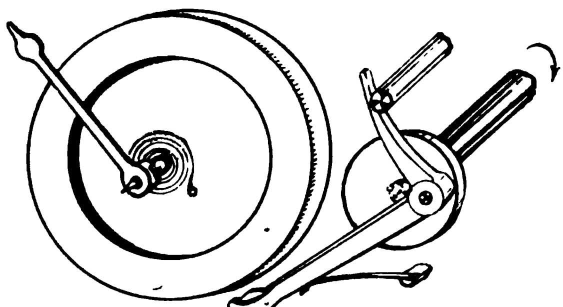


Fig. 200 _ Inertia tachometer

Cowey in the design of an instrument intended primarily for motor vehicles. This instrument takes the form of a milled edge wheel (Fig. 200), which is rotated by impulses from a pawl mounted on a crank on the driving shaft. The wheel is drawn back in the direction of the zero stop by the control spring, but owing to its inertia the wheel only travels a certain distance in the interval of time intervening between two successive impulses. When a steady state has been attained the backward motion between the impulses must equal the forward movement caused by an impulse. If the speed of the shaft increases then the impulses occur at more frequent intervals and the forward motion by an impulse is not entirely wiped out by the backward movement in the interval before the next impulse, so that there is a progressive forward motion of the wheel until a position is reached such that the increased torque due to the control spring is just sufficient to cause the wheel to slip back by an amount exactly equal to the forward movement caused by an impulse. There is therefore a definite mean angular position for

each speed, and the pointer is arranged with sufficient play to eliminate the oscillation of the wheel, whilst indicating this mean reading. The instrument is somewhat sensitive to fluctuations in the drive if this is of the flexible type, hence this should be made very stiff to avoid torsional oscillations.

*Calibration of Tachometers.*—The calibration, or checking of tachometers, can be effected by two methods : (1) counter and watch, or (2) stroboscopic observation. The counter method needs no explanation, except to point out that the calibration gear must run very steadily over definite periods to allow of sufficient time for counting. Stroboscopic methods are very convenient and accurate, since they depend essentially on the constancy of a tuning fork. The time of vibration of a steel fork can be approximately determined from the following formula, regarding each prong as a bar fixed at one end.

$$N=84{,}590\ a/l^2.$$

Where $N$=number of vibrations per second of the prime tone.
$a$=thickness in cms.
$l$=length in cms.

The approximate nature of the formula is due to the assumption that the bar is rigidly fixed at one end, whereas in practice the bar is bent into U, thus making the equivalent value of $l$ uncertain. Forks can easily be tested and adjusted by comparison by ear with a standard fork. The beats in the sound become distinct when the forks are very nearly in unison. Forks can, however, be obtained commercially within about one-tenth per cent of a specified frequency. When it is desired to verify a fork in the laboratory, the usual method is to use a dropping plate. In this method a very light quill of paper is stuck on the tip of one prong and the fork supported in a position such that the quill traces a line on a sheet of smoked glass which is allowed to fall freely in front of it. The number of vibrations in a given distance can be counted and the time interval found by calculation from the known value of acceleration due to gravity. The temperature coefficient of a steel fork amounts to 0·01 per cent per degree centigrade.

*Stroboscopic Method of Measuring Speed with Slits.*—The slit fork method utilises the persistence of vision when an object is viewed intermittently. A tuning fork is fitted with two plates at the ends of the prongs, which are perforated with narrow slits, as shown in Fig. 201. The vision through the slits will be interrupted twice every complete vibration of the fork. Consequently, if any rotating regular

figure or circle of equidistant dots are viewed through the slits when the fork is vibrating, the first momentary view will give an impression of a stationary disc, and if the speed of rotation has certain definite values, a corner or dot will have moved forward to the position occupied by the one previously observed, when the next coincidence of the slits occurs the disc will appear to remain quite stationary. The series of speeds at which this effect is apparent is given by the expression

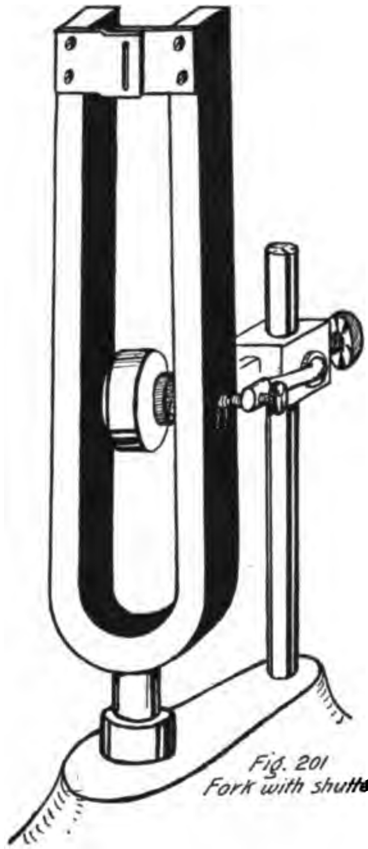


Fig. 201
Fork with shutters

$$n=120f/a$$

where $n$=speed of disc in R.P.M.
$f$=frequency of fork (complete vibrations per second).
$a$=number of corners or dots.

The figures repeat themselves for multiples of the speed, and with the elementary types of figures it is somewhat difficult to determine which multiple of the speed is under observation. For this reason it is usual to employ a standard disc (with a 50 D.V. fork), on which is printed a thirty point star, a hexagon, a pentagon, and a square. The figures which will appear to be motionless at any particular speed are given in Table VI. All other figures at this speed will, of course, be blurred.

## TABLE VI

TABLE OF SPEEDS FOR 50 D.V. TUNING-FORK IN REVS. PER MINUTE

| With Neon tube | With Shutters | 30-point Star | Other figures |
|---|---|---|---|
| 50 | 100 | Double | — |
| 100 | 200 | Single | — |
| 150 | 300 | Double | — |
| 166·7 | 333·3 | — | Triple Hexagon |
| 200 | 400 | Single | Triple Pentagon |
| 250 | 500 | Double | Double Hexagon—Triple Square |
| 300 | 600 | Single | Double Pentagon |
| 333·3 | 666·7 | — | Triple Hexagon |
| 350 | 700 | Double | — |
| 375 | 750 | — | Double Square |
| 400 | 800 | Single | Triple Pentagon |
| 450 | 900 | Double | — |
| 500 | 1000 | Single | Single Hexagon—Triple Square |
| 550 | 1100 | Double | — |
| 600 | 1200 | Single | Single Pentagon |
| 650 | 1300 | Double | — |
| 666·7 | 1333·3 | — | Triple Hexagon |
| 700 | 1400 | Single | — |
| 750 | 1500 | Double | Single Square—Double Hexagon |
| 800 | 1600 | Single | Triple Pentagon |
| 833·3 | 1666·7 | — | Triple Hexagon |
| 850 | 1700 | Double | — |
| 900 | 1800 | Single | Double Pentagon |
| 950 | 1900 | Double | — |
| 1000 | 2000 | Single | Single Hexagon—Triple Square—Triple Pentagon |
| 1050 | 2100 | Double | — |
| 1100 | 2200 | Single | — |
| 1125 | 2250 | — | Double Square |
| 1150 | 2300 | Double | — |
| 1166·7 | 2333·3 | — | Triple Hexagon |
| 1200 | 2400 | Single | Single Pentagon |
| 1250 | 2500 | Double | Double Hexagon—Triple Square |
| 1300 | 2600 | Single | — |
| 1333·3 | 2666·7 | — | Triple Hexagon |
| 1350 | 2700 | Double | — |
| 1400 | 2800 | Single | Triple Pentagon |
| 1450 | 2900 | Double | — |
| 1500 | 3000 | Single | Single Square—Single Hexagon—Double Pentagon |
| 1550 | 3100 | Double | — |
| 1600 | 3200 | Single | Triple Pentagon |
| 1650 | 3300 | Double | — |
| 1666·7 | 3333·3 | — | Triple Hexagon |
| 1700 | 3400 | Single | — |
| 1750 | 3500 | Double | Double Hexagon—Triple Square |
| 1800 | 3600 | Single | Single Pentagon |

TABLE VI—*continued.*

| With Neon tube | With Shutters | 30-point Star | Other figures |
|---|---|---|---|
| 1833·3 | 3666·7 | — | Triple Hexagon |
| 1850 | 3700 | Double | — |
| 1875 | 3750 | — | Double Square |
| 1900 | 3800 | Single | — |
| 1950 | 3900 | Double | — |
| 2000 | 4000 | Single | Single Hexagon—Triple Square—Triple Pentagon |
| 2050 | 4100 | Double | — |
| 2100 | 4200 | Single | Double Pentagon |
| 2150 | 4300 | Double | — |
| 2166·7 | 4333·3 | — | Triple Hexagon |
| 2200 | 4400 | Single | Triple Pentagon |
| 2250 | 4500 | Double | Single Square—Double Hexagon |
| 2300 | 4600 | Single | — |
| 2333·3 | 4666·7 | — | Triple Hexagon |
| 2350 | 4700 | Double | — |
| 2400 | 4800 | Single | Single Pentagon |
| 2450 | 4900 | Double | — |
| 2500 | 5000 | Single | Single Hexagon—Triple Square |
| 2625 | 5250 | — | Double Square |
| 2700 | 5400 | Single | Double Pentagon |
| 2750 | 5500 | Double | Double Hexagon—Triple Square |
| 3000 | 6000 | Single | Single Square—Single Pentagon—Single Hexagon |

It will be observed that the apparatus is especially adapted for giving points at intervals over the range for calibration purposes. Intermediate speeds cannot be measured, although slightly different speeds from the fixed values can be estimated from the apparent backward or forward creep of the disc in a measured interval of time.

Tuning-forks for stroboscopic methods are usually maintained electrically by a small electro-magnet between the prongs with a make and break contact on the side of the prong. A two-volt battery and less than a fifth of an ampere current is usually sufficient to maintain the vibration. The weight of the shutters on the end of the prongs affect the frequency of the fork, and they should therefore be fitted before the fork is adjusted.

Harrison and Abbot have devised a very convenient arrangement of the stroboscopic method in which the disc is observed by intermittent illumination. The fork is electrically maintained, as above described, while a contact operated by the fork is used to make and break the primary of an induction coil operating a neon discharge tube. The

complete arrangement is shown in Fig. 202. The illumination obtained is a faint red glow, but is quite sufficient if the disc and tube are placed in a box with an inspection hole. The advantages over the slit fork are considerable, since both the tachometer under test and the rotating disc are under observation simultaneously. The same diagram on the disc now corresponds to half the speed for the same frequency of fork, since the flashes of light only occur once for each complete vibration, whereas the slits will register twice in each vibration.

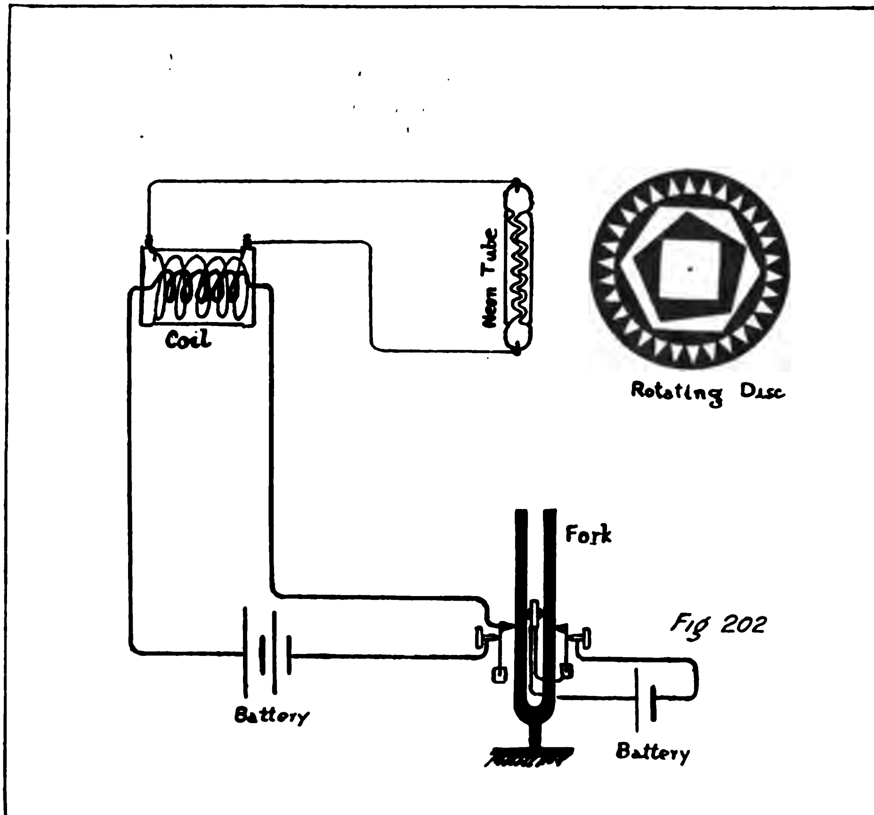



Fig 202

Mr. Mason, of the Cambridge Scientific Inst. Co., has designed a stroboscopic method which is portable and simple to use. He employs a source of light such as a Nernst lamp, projecting a beam of light on to the rotating part or disc, and interrupts the light by a rotating shutter fixed traverse to the path of the beam. The shutter is rotated by a simple form of sychronous motor controlled by a tuning-fork which is electrically maintained. A photograph of the fork and motor is shown in Fig. 203, the motor being shown enlarged in Fig. 204. The light is

intense and can be directed on to the object from a short distance. The stroboscopic method is an extremely accurate one and can be used for other purposes besides calibrating, such as, for instance, for observing the variation in speed during one revolution due to crank effort, etc.

*Synchronizing Fork.*—Messrs. Leeds and Northrup, of Philadelphia, have devised a method of obtaining constant and definite speeds for the calibration of tachometers without the necessity of manual adjustment. The instruments under test are driven through a series of gears, giving the approximate ratios off the shaft of a rotary converter. It is well known that an alternating current generator and synchronous motor will react upon each other and keep in step. In the Northrup device

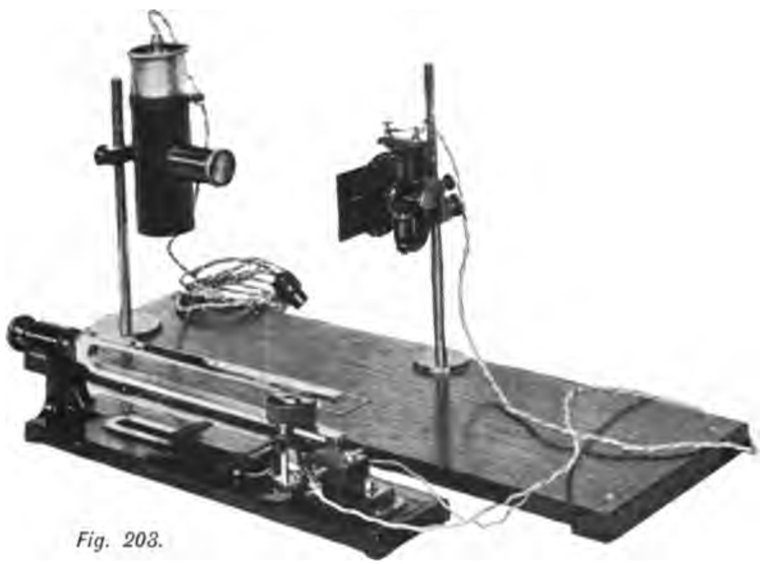


Fig. 203.

the rotating converter supplies alternating current to a synchronous load in the form of a tuning-fork and incandescent lamp. The fork holds the generator to a constant speed such that the frequency of the alternating current is equal to the frequency of the make and break on the prong as determined by the natural period of the fork. The scheme of connections is shown in Fig. 205.

The standard fork is arranged to operate at from fifty to seventy-five vibrations per second. In order to procure this range of rate of vibration, sliding weights are provided which are mounted upon the prongs of the fork. Slight variations in the rate of vibration of the fork can be accomplished by moving heavy springs along the prongs of the fork. These springs are moved by means of a screw, and the adjustment can

be made while the fork is in operation. This spring device is shown in the illustration (Fig. 206).

Flat brass plates are shown mounted upon the movable weights on the prongs of the fork. Slits are provided in these plates in order that it may be stroboscopically determined when the converter is running at the proper speed. It will be noticed that there is a vibrating contact device on each prong of the fork. One of these makes contact only at one end of its travel, and is in the circuit of the electro-magnet which actuates the fork. The other contact interrupts a circuit from the A.C. end of the rotary converter through an incandescent lamp shown mounted upon the base of the fork. The load which is thus thrown upon the converter is used in holding the converter in synchronism with the fork. The operation is as follows:

Fig. 204.

The fork is caused to vibrate at a rate corresponding to the frequency of the A.C. current delivered by the rotary converter when running at the desired speed. This is a comparatively simple operation made by means of a telephone. Assuming that the fork and converter are in synchronism, the function of the device is to maintain this synchronism despite changes of the D.C. voltage and of the load upon the converter, either of which would tend to change the speed of the converter.

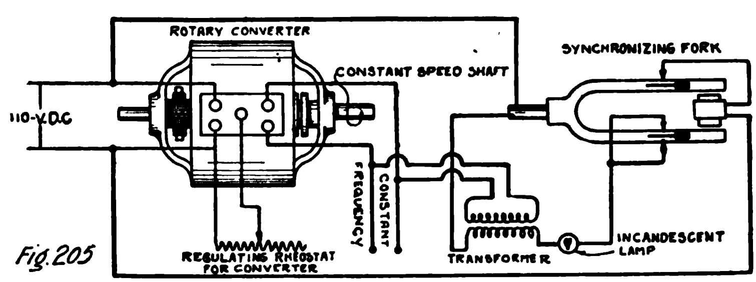



Fig. 205

It will be seen from an inspection of Fig. 205 that a circuit is taken from the A.C. end of the converter through an incandescent lamp and through the double contacting device on one prong of the fork. A

transformer is interposed in this circuit for two reasons. First, were it not for this transformer there would be a cross-connexion of circuits in the fork, as both the A.C. current from the converter and the D.C. driving current pass through the fork and also through the same windings in the armature of the converter. Second, the transformer raises the A.C. voltage to 110 volts, or a multiple of 110, in order that lamps of a standard voltage may be used for the regulating load. Assuming, now, that the converter and fork are in synchronism, for every cycle of the A.C. voltage curve two contacts will be made at the fork, and two impulses will be sent through the lamp. These contacts may take place at any point on the voltage curve, but so long as there is no tendency to alter the speed of the converter, they will always take place at the same point. Thus a certain voltage is impressed across the lamp during a brief interval twice in each cycle. This lamp is thus a load upon the converter, the

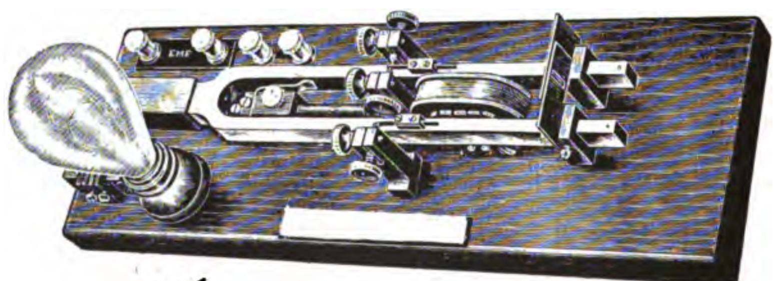


Fig. 206

magnitude of this load depending upon the voltage impressed upon the lamp.

Now assume that either a change of D.C. voltage or a change of load upon the converter should occur. The speed of the machine would tend to change. This would tend to throw the A.C. current out of synchronism with the fork. The result would be that the voltage impressed across the lamp would be different, because the contacts would be made at different points on the voltage curve. If the speed were tending to increase, the contacts would occur nearer the top of the voltage curve, impressing a greater voltage across the lamp load, and thus putting a greater load upon the machine and slowing it down. Should the speed be tending to become less, a reverse result would occur, both results acting to keep the A.C. current in rigid synchronism with the fork. Thus the speed regulation takes place automatically, until the forces tending to change the speed of the converter become excessive.

An absolutely steady source of E.M.F. is not necessary for the success-

ful operation of the converter. Fluctuations in the D.C. voltage amounting to 5 to 7 per cent from the nominal value can be very well cared for.

While one lamp is shown only mounted on the fork base, it is sometimes necessary to use more than one lamp. In this case, the several lamps are generally connected in parallel. The number of lamps which it is necessary to use depends upon the amount of change of the load, either electrical or mechanical, which is put upon the machine. For example, a machine with a normal rating of 500 watts was controlled with a load of 40 watts, when the useful load varied between 330 and 270 watts. A regulating load of about 340 watts was required, when the useful load upon the same machine varied between 360 and 60 watts. The speed regulation claimed is within the accuracy of the fork, that is 0·1 per cent, provided the load put on to the shaft is not sufficient to break synchronism.

The frequency of the fork when once set can be found by stroboscopic comparison with a standard, and all the changes for calibration purposes are made by means of gears.

## SECTION II

### Velocity of Trains

The linear velocity of any moving object is somewhat difficult to determine by direct measurement of time and distance, and is only attempted in special circumstances, such as test runs on trains, motor-car races, etc.

The Le Boulengé method, devised about 1877, depends upon the action of the locomotive wheel depressing two triggers at a known distance apart, usually about forty-four metres. These triggers are arranged at the side of the rail, as shown in sketch (Fig. 207). The depression of the trigger releases a projection holding the end of a wire which communicates with the recorder.

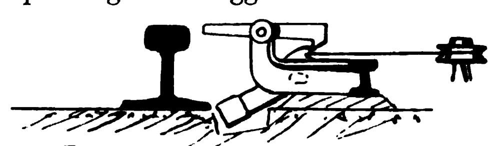


Fig 207. Trigger device

*Boulengé Recorder.*—The principle of this recorder is illustrated by the diagram in Fig. 208. It consists of a disc pivoted freely on an horizontal axis, which can be rotated by the weight suspended from a string passing over a pulley fixed to the shaft. The disc is initially wound up to a stop and held in this position by a lever connected to the wire from the first trigger. When this wire is released the disc starts to rotate

and continues to turn until the second trigger is depressed by the train. This lever arm then comes into contact with the edge of the disc and instantly arrests its motion. The time interval can be calculated from the angle turned through as observed by a pointer. This method of timing is somewhat primitive and rarely used at the present day.

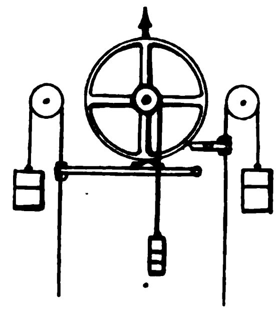


Fig 208_ Recording mechanism

*Siemens Speed Recorder.*—Siemens and Halske introduced an electrical method in conjunction with a clock-driven tape chronograph. In this speed recorder the two contact makers (Fig. 209), are clamped to the underside of the rail, and the deflection of the rail between the two clamps due to the weight of the wheel depresses a diaphragm forcing mercury into a contact chamber. A section of the device is shown in Fig. 210.

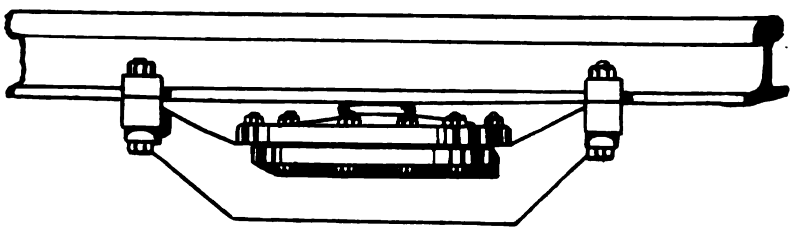


Fig 209_ Contact box on rail

The mercury escapes through a small hole in the contact chamber, and this gives a longer duration of contact. The chronograph is of the usual clock-driven type recording on a paper ribbon.

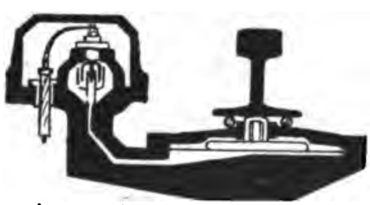


Fig 210. Section of contact box

If a dynamometer car is used on a train it is usual to employ for simplicity a tachometer driven by a special wheel of known diameter fixed to the car, and to calibrate the tachometer to indicate speed directly. The tachometer, of course, may be any one of the previously described types.

## SECTION III

### Velocity of Aircraft

Instruments for indicating the speed of aircraft relative to the earth have not yet been devised, and the velocity must be determined either by optical observations of the ground or assumed to be the speed relative

to the air. The methods of measuring air speed are identical in principle with those already described for measuring the velocity of fluid flow in pipes with pressure indicators adapted to be portable.

*Pitot Tube.*—The Pitot tube air-speed indicator is very extensively used in this country. The pressure indicated obeys the law

$$p=\tfrac{1}{2}\rho\, V^2$$

where $p$ = pressure differences
$\rho$ = density
$V$ = velocity

provided that the static tube complies with simple conditions already specified on page 96.

This method of air-speed measurement has the great advantage of not requiring individual calibration for each tube and the instruments are therefore absolutely interchangeable. The Pitot head is manufactured in several convenient forms to facilitate fitting, and one well-known type is illustrated in Fig. 211. This fitting is arranged for attachment to a strut. The tube must not, of course, be placed in any dis-

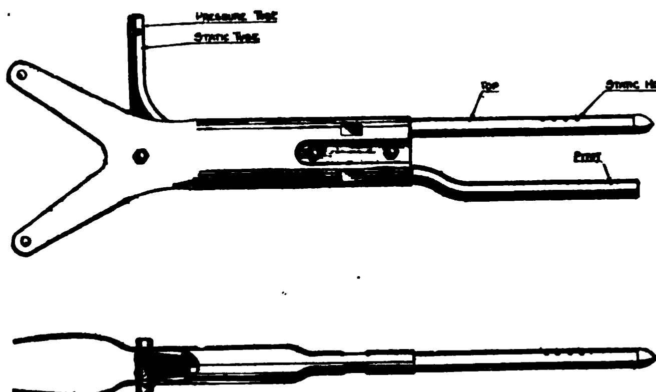


Fig. 211 _ Pitot Tube

turbed region such as that due to propeller wash or to the air flow over the wings. The usual position in the case of a biplane for minimum disturbance is about one-third of the way down a strut. The tube should always be placed well in front of any structural part of the machine, since experiment shows that the disturbed region may extend ahead as well as astern of wings, etc.

As previously pointed out, the pressure difference is comparatively small even at the high speeds at which modern machines fly. In Table VII is given some figures for the head obtained over the usual range of velocities.

TABLE VII

| Air Speed in M.P.H. | Pressure. Ins. of water | Air Speed in M.P.H. | Pressure. Ins. of water. | Air Speed in M.P.H. | Pressure. Ins. of water. |
|---|---|---|---|---|---|
| 30 | ·44 | 75 | 2·75 | 120 | 7·05 |
| 35 | ·60 | 80 | 3·13 | 125 | 7·65 |
| 40 | ·78 | 85 | 3·54 | 130 | 8·28 |
| 45 | ·99 | 90 | 3·97 | 135 | 8·92 |
| 50 | 1·22 | 95 | 4·42 | 140 | 9·60 |
| 55 | 1·48 | 100 | 4·90 | 145 | 10·30 |
| 60 | 1·76 | 105 | 5·40 | 150 | 11·02 |
| 65 | 2·07 | 110 | 5·93 | 155 | 11·76 |
| 70 | 2·40 | 115 | 6·48 | 160 | 12·54 |

For this reason the pressure indicator must be very sensitive, and rubber or silk diaphragms are generally used in the differential pressure gauges. The simplest and oldest gauge is the Ogilvie; this is shown in Fig. 212. It consists of a thin rubber diaphragm about four inches in diameter, to the centre of which is fastened a silk thread. This thread passes over a pulley and is wound around the pointer spindle, pressure is admitted on top of the diaphragm, the glass front of the instrument being made air-tight for this purpose; the static tube communicates with the under-side of the diaphragm. The movement of the diaphragm uncoils the thread against the pull of a hairspring, which keeps the string taut. The controlling force is due to the elasticity of the rubber diaphragm, and no spring is fitted except that on the pointer spindle. Rubber diaphragms are liable to perish when subject to extreme temperature variations, consequently leather, or thin metal diaphragm instruments are sometimes used.

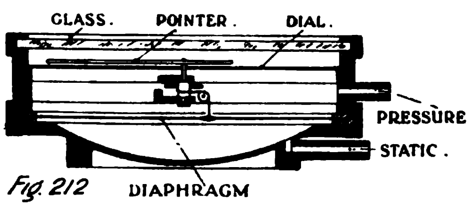


Fig. 212

*Clift Differential Indicator.*—This instrument is more elaborate than the above described, and a section is shown in Fig. 213. The diaphragm presses against a cantilever spring, the deflection of this spring is magnified by a bell-crank lever and slotted quadrant geared to the pointer. The quadrant and gear are shown separately in Fig. 214.

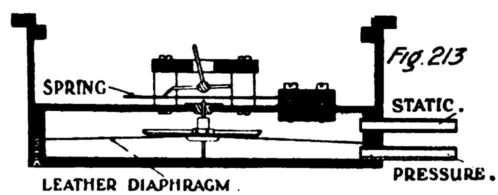


Fig. 213

The diaphragm exerts a controlling force when deflected, and in addition the magnification of the lever system is not constant, hence each indicator must be graduated for the known square law of the Pitot tube. Recalibration is also desirable at frequent intervals in accurate work.

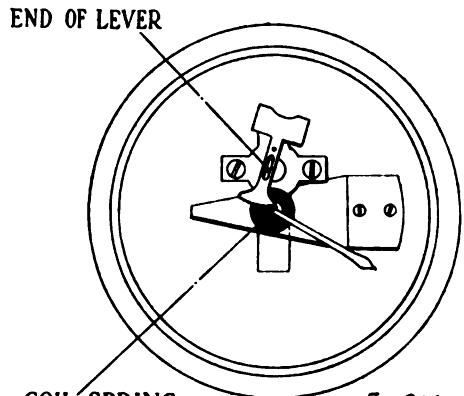


Fig. 214

*Venturi Air-speed Indicators.*—The small pressure difference obtained with the Pitot tube has directed attention to the various means of obtaining increased suction instead of static pressure, as an increased pressure difference would enable a more robust indicator to be used.

Clift and others employed a suction head many years ago, but the modern tendency is towards Venturi tubes, since by this means a very considerable suction can then be obtained in a simple manner. The single Venturi consists of two frustrums of cones joined at their smallest diameter, as shown in sketch (Fig. 215).

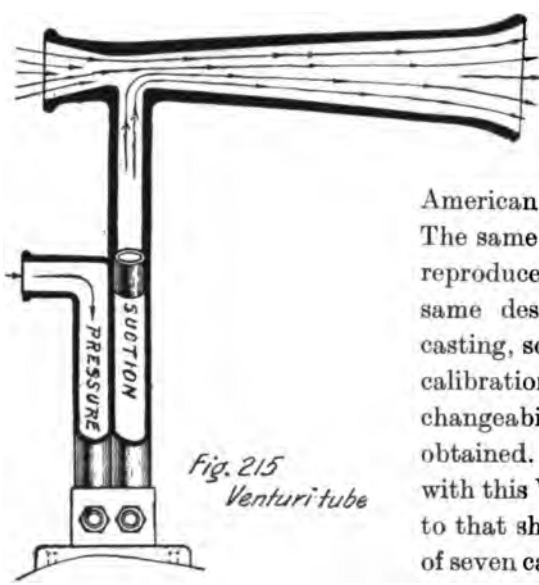


Fig. 215 Venturi tube

A typical calibration curve for a well-designed form of Venturi tube, used by the American Air Force, is shown in Fig. 216. The same calibration curve is not strictly reproduced by duplicate tubes of the same design, even when made by die casting, so each outfit requires individual calibration for accurate work. Interchangeability of the parts is not readily obtained. The indicator generally used with this Venturi is similar in construction to that shown in Fig. 163. Two batteries of seven capsules are connected to opposite ends of the quadrant arm (to eliminate acceleration effects). A stop engages with a projection on the edge of one of the capsules cutting out a certain number at a definite deflection, thus making the gauge less sensitive at high speeds and the scale more uniform. This instrument does not appear to be more accurate than those used for the Pitot

tubes previously described. The Venturi tube of the above form is more sensitive to angles of yaw than the Pitot, and Fig. 217 is a

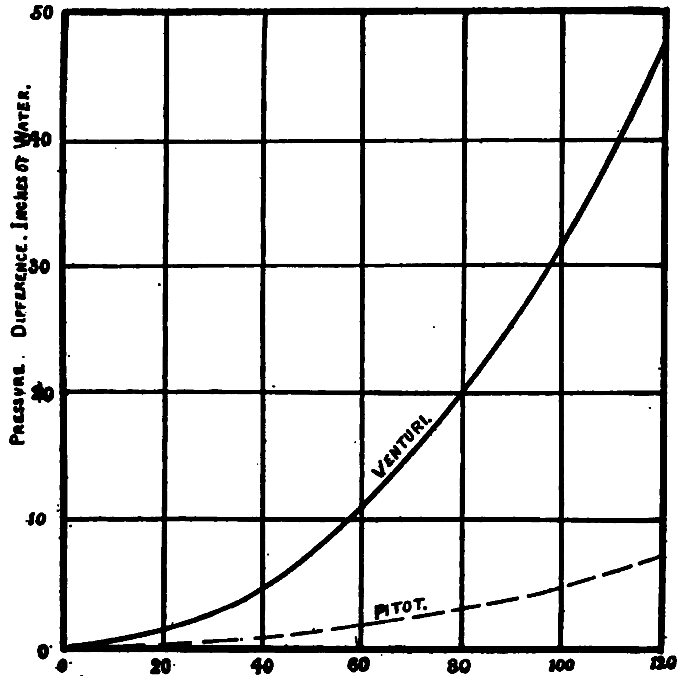



Fig. 216

typical curve for effect of yaw for a tube with a throat ratio of 6 to 1 in area. The pressures are expressed in terms of the pressure obtained when the tube is along the wind. An error of 6 per cent will be observed

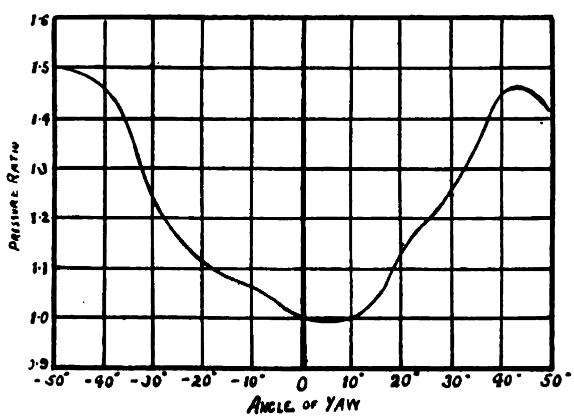



Fig. 217 – Effect of yaw on Venturi

at an angle of $-10°$. The assymmetry of the curve is quite usual for a Venturi, although the design of the tube is practically symmetrical.

Venturi tubes with double throat have been developed, but the same objections as to lack of reproducibility apply also to double tubes. Such Venturis are of use in special investigations, where low speeds must be measured, and special calibration is a matter of course for whatever type of instrument is employed in such work.

*Double Venturi.*—It has long been realised that if two Venturis of appropriate dimensions are arranged with the diverging cone of one in the zone of greatest suction of the other the suction obtained in the second tube is greatly amplified. This mode of construction has been used for petrol lift and air-driven gyroscopes on aircraft. The air-speed Venturi is a miniature form of this double Venturi, and the form adopted by the German Air Service is shown in section in Fig. 218. The two tubes have an area ratio of approximately 2½ to 1. The suction obtained is considerably greater than that of a single throat Venturi, and a typical curve for this type is shown in Fig. 219.

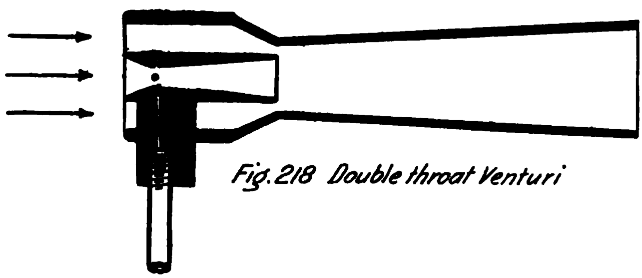


*Fig. 218 Double throat Venturi*

In this form the Pitot head on the impact side has been abandoned, as the additional pressure due to the Pitot is negligible in comparison with the suction. It will be observed that the calibration curve does not agree with the square law. The indicator has only one capsule, about three inches in diameter, which is connected directly to a quadrant operating the pointer by a gear wheel.

*Hooded Venturi.*—The American Naval Air Service has conducted a research into the design of a Venturi which would minimise the errors due to yaw and the effect of rain getting into the Venturi head. They utilised the well-known fact that the suction at the back of a cylinder moving through the air is almost independent of its orientation for small angles of rotation and of yaw. The divergent cone of the Venturi, which is of the double throat type, is therefore communicated to a short cylinder in the down wind side of which two slits have been cut. The inlet side of the Venturi is taken from an oblong box, which has a narrow slot in front, a gauge screen being placed just within this opening

to prevent rain reaching the throat. The complete instrument is shown in Fig. 220. The effect of yaw has been reduced to a negligible amount

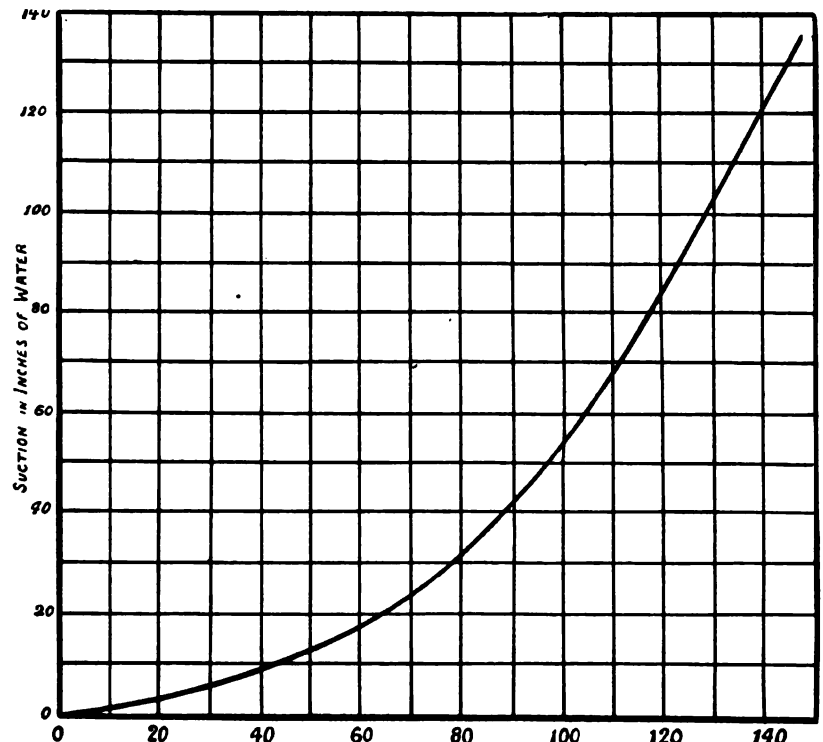



Fig. 219

for angles up to 10°, as shown in Fig. 221, and the error due to pitching is only 3 per cent for 10° of downward angle, this being largely due to shadowing of the slot, and even this could, no doubt, be reduced by slight modifications. The calibrations of this Venturi is said to be strictly proportional to the square of the velocity and to have the value

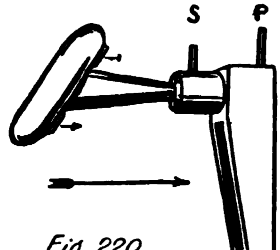



Fig. 220
Hooded Venturi

$p = 0{\cdot}0053\ V^2$.

$V$ is in miles per hour.

$p$ differential pressure in inches of water.

A serious consideration with modern aircraft of high "ceiling" is the dependence of all of the above described instruments upon the density of the air. The calibration is affected to the extent shown in Table VIII.

TABLE VIII

| Isothermal Ht. (feet) | PERCENTAGE CORRECTION TO BE ADDED TO A.S.I. READINGS AT GROUND TEMPERATURE. | | | | |
|---|---|---|---|---|---|
| | −10°C. | 0°C. | 10°C. | 20°C. | 30°C. |
| 0 | −4·6 | −2·8 | −1·1 | + ·7 | + 2·4 |
| 1,000 | −3·2 | −1·3 | + ·5 | 2·2 | 3·9 |
| 2,000 | −1·7 | + ·2 | 2·0 | 3·8 | 5·6 |
| 3,000 | − ·1 | 1·7 | 3·6 | 5·4 | 7·2 |
| 4,000 | +1·4 | 3·3 | 5·2 | 7·0 | 8·8 |
| 5,000 | 2·9 | 4·9 | 6·8 | 8·6 | 10·5 |
| 6,000 | 4·5 | 6·5 | 8·4 | 10·3 | 12·2 |
| 7,000 | 6·1 | 8·1 | 10·1 | 12·0 | 13·9 |
| 8,000 | 7·7 | 9·8 | 11·8 | 13·7 | 15·6 |
| 9,000 | 9·4 | 11·4 | 13·5 | 15·4 | 17·4 |
| 10,000 | 11·0 | 13·1 | 15·2 | 17·2 | 19·2 |
| 11,000 | 12·7 | 14·8 | 16·9 | 19·0 | 21·0 |
| 12,000 | 1[illegible]·4 | 16·6 | 18·7 | 20·8 | 22·8 |
| 13,000 | 16·2 | 18·4 | 20·5 | 22·6 | 24·7 |
| 14,000 | 17·9 | 20·2 | 22·4 | 24·5 | 26·6 |
| 15,000 | 19·7 | 22·0 | 24·2 | 26·4 | 28·5 |
| 16,000 | 21·5 | 23·8 | 26·1 | 28·3 | 30·4 |
| 17,000 | 23·4 | 25·7 | 28·0 | 30·2 | 32·4 |
| 18,000 | 25·2 | 27·6 | 29·9 | 32·2 | 34·4 |
| 19,000 | 27·1 | 29·5 | 31·8 | 34·2 | 36·4 |
| 20,000 | 29·0 | 31·4 | 33·8 | 36·2 | 38·5 |
| 21,000 | 30·9 | 33·4 | 35·8 | 38·2 | 40·5 |
| 22,000 | 32·9 | 35·4 | 37·9 | 40·3 | 42·6 |
| 23,000 | 34·9 | 37·4 | 39·9 | 42·4 | 44·8 |
| 24,000 | 36·9 | 39·5 | 42·0 | 44·5 | 46·9 |
| 25,000 | 38·9 | 41·5 | 44·1 | 46·6 | 49·1 |

The error at twenty-thousand feet amounts to 35 per cent at ordinary temperature. It might be mentioned that since the aeroplane speed is also dependent upon density the stalling speed always has the same numerical value on the indicator. This advantage is, however, very trivial, since stalling on any stable machine is not a source of danger at the heights when density effect is appreciable.

*Robinson Cup Air-speed Indicator.*—The density connection due to altitude with Pitot tube air-speed indicators is a very inconvenient correction to apply, especially in flight. Calculators have been devised for simplifying the operation, but these devices have to presuppose in their design a definite temperature lapse rate with altitude. The correct value of air speed is then obtained by the use of a factor applied to the

apparent speed calculated from the altimeter reading. Two other methods of reducing the error are possible : (1) automatic compensation of the pressure gauge used with the Pitot tube by the use of variable magnification controlled by a capsule full of air ; (2) the use of vane type air-speed indicators whose indications can be made almost independent of the density. The German Air Service has employed in addition to the Pitot and Venturi tubes already described, an instrument of this type consisting of a Robinson cup anemometer driving a centrifugal tachometer. A section of the instrument is shown in Fig. 222. The four small cups are carried on arms fixed to the vertical spindle. A crossed pendulum on the spindle operates the pointer through a train of wheels ; the mechanical arrangement being similar to that commonly employed in continental forms of tachometers.

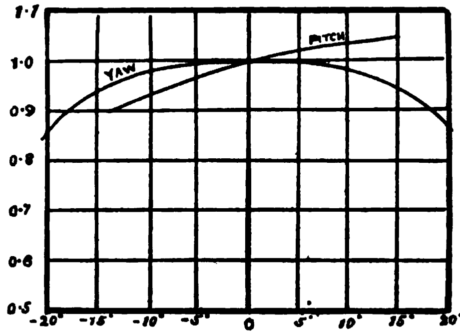


Fig. 221 – Effect of pitch and yaw on hooded Venturi

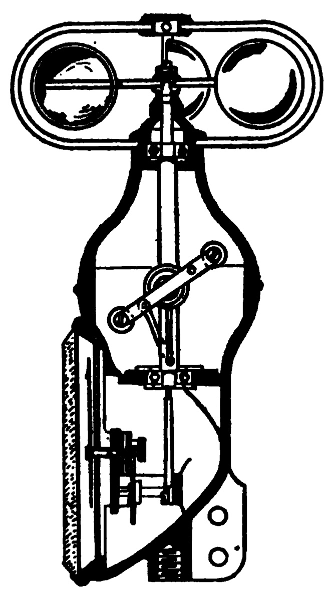


Fig. 222 – Air speed indicator

Dr. W. Wilke has investigated the operation of this instrument, both experimentally and theoretically, and although the assumptions upon which the theory is based are scarcely valid his experimental data are of considerable interest. It has long been known that Robinson cup anemometers show a variation of the ratio coefficient of cup speed to wind speed with the velocity of rotation, and that the coefficient approximates to a constant value with increase in speed. Wilke also finds this variation in the coefficient, as shown in Table IX.

The variation, although of considerable moment to metrologists employing integrating instruments, is of but slight importance in aircraft work, since the calibration of the tachometer takes account of the actual coefficient at each speed. It serves, however, to show the influence of friction, and from an analysis of the data the effect of density is deduced by

Wilke to be extremely small at high speeds. Direct experiments are, however, required to finally establish the negligible effect assigned to the change in density.

TABLE IX

| Air Speed (metres per second) | Speed of cups (metres per second) | Coefficient |
|---|---|---|
| 14·4 | 4·40 | 3·27 |
| 17·7 | 5·57 | 3·18 |
| 20·6 | 6·64 | 3·10 |
| 23·4 | 7·48 | 3·00 |
| 26·1 | 8·43 | 3·10 |
| 28·7 | 9·35 | 3·07 |
| 31·5 | 10·22 | 3·08 |
| 34·2 | 11·27 | 3·04 |
| 37·3 | 12·22 | 3·04 |
| 40·1 | 13·23 | 3·03 |
| 43·4 | 14·49 | 3·00 |

A determination of the variation of friction with temperature of the tachometer portion was made experimentally, and the coefficient was found to vary, as shown in Table X.

TABLE X

| Temperature. | +18° | −10° | −15° | −50° |
|---|---|---|---|---|
| Moment of friction (in gram centimetres) . . . | 0·855 | 0·888 | 2·58 | 5·10 |
| Calculated coefficient of friction . . . . | 0·024 | 0·025 | 0·071 | 0·141 |

This variation is largely due to the increase in viscosity of the oil. It appears unnecessarily great and could probably be reduced by the use of solid lubricants, such as graphite bushes, etc. The indication of the instrument for the same values of the speed and density of the air, but with the temperature of the tachometers[1] at +18° C and −50° C only varied by 6 per cent. This experiment certainly lends support to the theoretical conclusion that the effect of density is small.

[1] Enclosed in cold box with cups projecting.

It may be remarked that this application of the Robinson cup to an air-speed indicator is not new, and the arrangement has long been used by the British Navy for wind correction in gunnery. The tachometer in this instrument is of the magnetic type, which is probably superior to the other on account of less frictional resistance.

*Hot Wire Anemometers.*—The principle that the heat loss from a wire is dependent on the velocity of the gas stream past it has been utilised by several investigators as the basis of a method for measuring wind velocity. In the simplest type of instrument the hot wire forms one arm of a Wheatstone bridge, the other three arms of which are made of heavy section wire of negligible temperature coefficient. The temperature, and hence the resistance of the wire, is maintained constant at all values of the wind speed by varying the watts dissipated in the wire to maintain balance or the watts are kept constant and the temperature allowed to vary. In the former case the watts supplied is a measure of the wind velocity, in the latter the out of balance deflection of the galvanometer in the bridge circuit. For precision work it is preferable to employ a Kelvin double bridge, as this permits of a robust platinum wire of comparatively low resistance.

The researches of King and others have shown that the heat loss is related to the velocity, etc., by the following equations :—

*For low velocities*

$$H = 2\pi K \theta_0 / \log \frac{b}{a}$$

*For high velocities*

$$H = K\theta_0 + 2\sqrt{\pi K s \delta a}\ V^{\frac{1}{2}} \theta_0$$

Where $H$ is the heat loss per unit length of the wire,

,, $K$ is the thermal conductivity of the gas,

$\delta$ ,, density,

$s$ ,, specific heat of unit mass,

$\theta_0$ is the temperature difference between the cylindrical wire radius $a$ and the unheated fluid. $b$ is given by $K\ \rho^{\ 1\cdot\gamma}/(s\delta V)$, in which $\gamma$ is Euler's constant 0·5771.

The particular ranges over which the above formulæ are applicable is determined by the values of $Vd$, where $V$ is the wind velocity and $d$ the diameter of the wire.

When the product $Vd$ is less than 0·0187 measured in cms. and seconds the equation for low velocities is applicable, and for values of $Vd$ above this the equation for high velocities.

It will be observed that the heat loss varies roughly as the square

root of the product of velocity and the density for high velocities. Consequently the instrument is most sensitive for low wind velocities, and here it finds its most promising field of application. It must, however, be remembered that the hot wire sets up convection currents, and this is a complication when extremely low velocities have to be measured.

The hot wire anemometer has been tried on aircraft, but here the wind velocities are so high that the instrument at present does not show sufficient advantages over the other methods to justify the complication that it entails. In its simplest form the anemometer is not compensated for temperature changes of the air, and consequently some observers have effected this compensation by making all the arms of the same material, but shielding the two opposite arms from the wind stream. This arrangement admits of a simple deflectional instrument by keeping the watts dissipated in the bridge constant.

The rapid contraction of the scale of a hot wire anenometer with increasing velocities of flow is frequently a disadvantage. The writer partially overcame this defect by utilising the fact that the pressure depression at the throat of a Venturi varies as the square of the stream velocity.

If then a small bore branch circuit is connected across between the normal section and the throat the flow through this parallel circuit will vary as the square of the velocity of the main stream (being proportional to the pressure difference at the ends of the tube).

The hot wire was inserted in the branch circuit, so its indications varied almost proportionally to the velocity of the main stream and not the square root of this velocity.

The hot wire anemometer has been tested for use in the measurement of liquid flow, but it was found applicable over only a limited range of velocities. The author has tried various forms of hot wire anemometer and has come to the conclusion that although admirable as an instrument of research, it has not yet reached the stage of a direct reading appliance available for general use.

## SECTION IV

### Methods of Damping the Oscillations of the Moving System of an Instrument

If an instrument is to perform its function properly it must be able to give a definite indication at all times independent of whether the quantity measured is fluctuating or the instrument subject to vibration from external sources. Trouble due to oscillations of the indicator

pointer is a frequent one in engineering work, and particularly so with aeronautical instruments. When the period of vibration to which the instrument is subject happens to coincide with the natural rate of the moving part the oscillations become very large, and it is usually impossible to read the instrument. Damping is also required in cases where the fluctuations in the quantity to be measured are rapid, it may be difficult to read the instrument, and the excursions of the hand may indicate a much greater amount of variation of the quantity than really takes place. If the mean reading is required the instrument must be damped and the damping should be of a particular kind, as Sir Horace Darwin pointed out in the first Wilbur Wright Memorial Lecture.

The essential features of satisfactory damping are that no force should be applied to the moving part whilst it is at rest, but as soon as it moves a force should act opposing the movement. Friction at the joints damps the instrument, but it does not fulfil the above conditions and is bad. The force should be small when the movement is slow, and it should be increased when the movement becomes more rapid. The most usual method is to immerse the moving part, or a paddle fixed to it, in a liquid more or less viscous, or the paddle can be replaced by a fan in the air. Another method is to damp by the movement of a copper plate between the poles of a magnet (Fig. 223). If a Pitot tube is used, the flow of air through the connecting tubes damps the instrument.

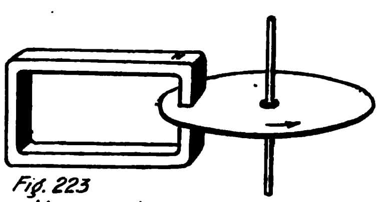


Fig. 223
Magnetic damper

Mr. A. Mallock has proved that in order to obtain a true mean reading with an instrument the damping force should be proportional to the velocity of its index. When the damping force varies as the square of the velocity there may be no error or there may be a considerable error. Taking a particular case, suppose that the quantity to be measured remains at eighty for two-tenths of a second, and then suddenly increases to one hundred and forty and remains at that amount for one-tenth of a second, and then it goes back to eighty and remains at that amount for two-tenths of a second, and that this rapid oscillation goes on indefinitely. Suppose, also, that the instrument is damped by a force which varies as the square of the velocity of the index, and that it is so much damped that the hand appears to remain at rest. The reading of the instrument will be ninety-two and the true mean in reality is one hundred, hence an error amounting to 8 per cent is produced—by no means a small error. The diagram (Fig. 224) gives the

supposed variations of the quantity as it would be recorded on a moving sheet of paper, and gives the true mean and the instrument reading.

The mathematical equation for the general case can be readily calculated :—

Suppose that the divisions on the scale are equally spaced and that each space corresponds to an equal increment in the quantity to be measured ; also that the quantity to be measured is given by a reading $a$ on the scale and that it suddenly changes to $b$. The hand will begin to move from reading $a$ to reading $b$ with a velocity $v$, and we will assume

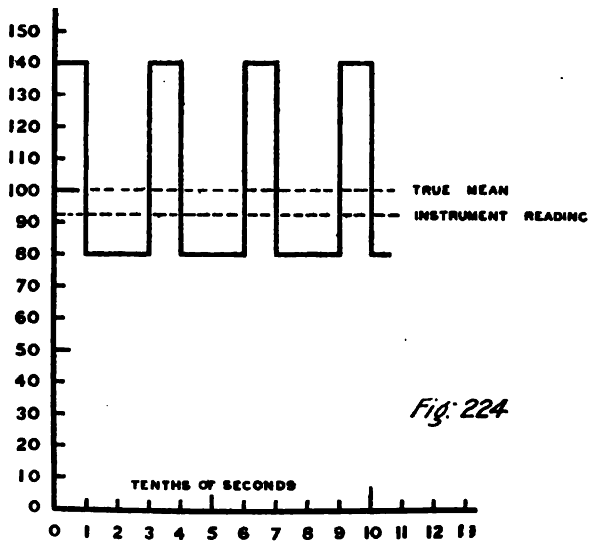



Fig. 224

that the damping force varies as $v^2$. This damping force must be equal to the force acting on the moving parts of the instrument which tend to move the hand from scale reading $a$ to $b$. This force in an instrument with a uniform scale will generally be proportional to the difference of $a$ and $b$, and it will be assumed that this is the case. Hence the force on the hand varies as $b-a$, and this is balanced by the damping force. That is

$$b-a=kv^2 \text{ ——(1)}$$

where $k$ is a constant.

Now consider what the amount of movement will be for a time $t$ which is so short that $v$ may be supposed to remain constant. Let $s$ be the space moved through by the hand. Then—

$$s=vt=\frac{t\sqrt{b-a}}{\sqrt{k}} \text{ ——(2).}$$

Now take a case similar to that indicated in Fig. 224, so that the

quantity to be measured remains at $a$ for the short time $t$ and at $b$ for the short time $t'$. The true mean

$$M=\frac{ta+t'b}{t+t'} \text{ ——(3).}$$

Let $m$ be the mean reading with the square law damping. Then in order that the hand should appear to remain at rest at this point, or rather that it should have a small and equal oscillation on both sides of it, the amount it moves up during $t$ must equal the amount it moves down during $t'$. From equation (2) we get :—

$$\sqrt{\underline{m-a}}\quad t=\sqrt{\underline{b-m}}\quad t' \text{ ——(4).}$$

so that

$$m=\frac{t'^2b+t^2a.}{t^2\;\;+t'^2}$$

It follows that $m$ can only equal $M$ when $t$ and $t'$ are equal.

If the damping force varies as $v$ and not as $v^2$ equation (2) becomes $s=\frac{t(b-a)}{k}$ and equation (4) becomes $\underline{m-a}\,t=\underline{b-m}t'$ $m=\frac{ta+t'b}{t+t'}=M$ for all values of $t$, $t'$, $a$, and $b$.

In the magnetic method of damping, the force varies as the velocity and the true mean is obtained. With liquid and air damping the force varies as the square of the velocity, unless the movement is extremely slow, when it varies nearly as the velocity.

Probably the simplest instrument mechanically used on aircraft is the Pitot tube and manometer. Now it frequently happens that the tubes transmitting the pressure have to be carried a considerable distance so as to permit the manometer to be placed in a convenient position for reading, and the dimensions of the tubing have a considerable influence on the damping obtained. If it is found advisable to have a large amount of damping in the manometer it is best to have long tubes of large diameter. This gives the correct form of damping. Short tubes of small diameter will also give a large amount of damping, but in this case the damping force will vary as the square of the velocity of the air in the tube and the reading will not necessarily be the true mean. For the same reason it is inadvisable to cause damping by throttling the passage of the air by closing a valve, or by means of letting it pass through a small hole in a plate.

Engineering instruments in general are more complicated, and it frequently happens that the damping obtained is due to the sum total effects of ($a$) solid friction force due to the friction between pivots and jewels ; ($b$) fluid frictional force due to the retarding action of the medium

in which the system swings ; and (*c*) electro-magnetic retarding force due to the production of electrical eddy currents. With moving coil instruments and permanent magnets it is a comparatively simple matter to obtain electro-magnetic damping by having the former, upon which the coil is wound, of metal. For galvanometers in which an aperiodic motion is frequently desired the former is sawn through at one place and the gap bridged by a fine wire of the requisite electrical resistance. When the instrument is of such a type that the presence of a powerful electro-magnet is inadmissible, air or liquid damping is employed. An air-damper requires accurate construction if it is to be effective, as it depends for its action upon the compression of air on the advancing side of a vane and the rarefaction on the receding side. The effect is negligible n open air and very slight in a chamber unless the leakage around the vane is very small.

A type of air damper commonly used in electrical instruments is that shown in Fig. 225. It consists of two very light symmetrically disposed vanes, which are enclosed in chambers made as nearly air-tight as possible. These vanes are formed of very thin metal stiffened with ribs stamped into them and by the edges which are bent over to conform to the surface of the side walls of the chambers. The one form of damping which has to be rigorously avoided in any instrument is that of solid friction at the pivots. If present it produces an uncertainty in the readings which invariably increases with prolonged use of the instrument, and it has the disadvantages of being independent of the velocity of the moving system and of its displacement.

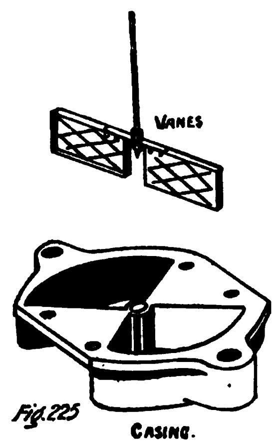
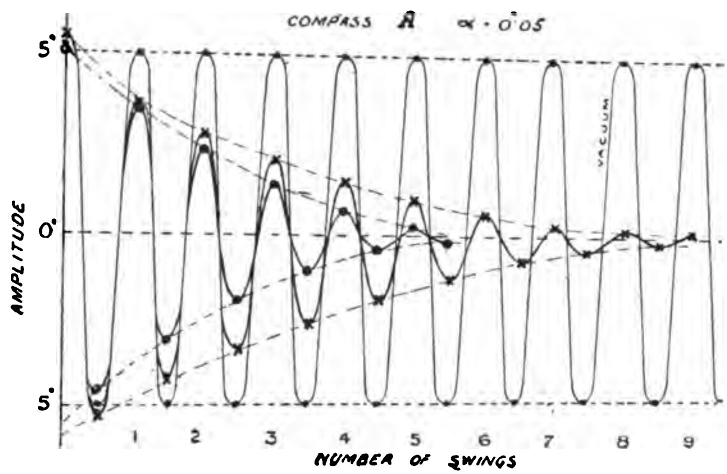


Fig. 225

But little quantitative data are available as to the magnitude of the damping effects existing in standard types of instruments. The case of the prismatic compass, an instrument with the most elementary moving system, has been worked out by Mr. F. E. Smith, F.R.S., whose conclusions as regards the various forms of damping obtained in this instrument are quoted below. He investigated the amplitude of swing of a compass needle under various conditions, and two of the curves obtained are shown in Fig. 226. The first set of curves $A$ are typical of those obtainable with a good compass, i.e. one with negligible friction error at the pivot ; while the set $B$ refer to one with big frictional error. These results were obtained as follows :—

The moving system of the compasses were set oscillating in the usual manner, and the amplitude of each swing was noted until the systems came nearly to rest. For a maximum initial amplitude of 5° compass $A$ made five complete oscillations before the amplitude was reduced to 0·2°, while compass $B$ made only two complete swings. The amplitude and number of swings have been plotted in the curve indicated



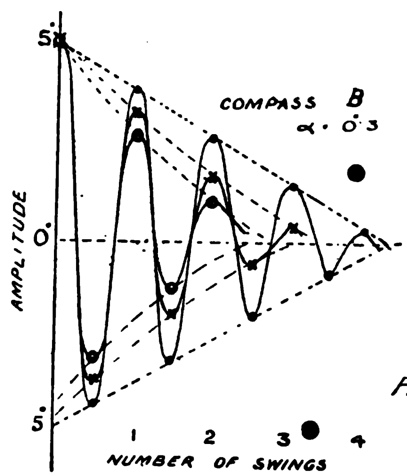




Fig. 226

by the points marked ⊙ in the diagrams. The electro-magnetic damping was next eliminated by removing the swinging systems from the metal cases and enclosing in cardboard boxes covered with mica. Repeating the experiment, compass $A$ made eight complete swings, and compass $B$ three complete swings. The results are plotted and may be identified by the points marked × in the diagrams. The systems were then placed in a glass jar and the air exhausted, the pressure being reduced to 0·01 mm. Similar sets of observations starting with the same initial amplitude gave for compass $A$ at least one hundred complete swings, and for compass $B$ four complete swings. The results may be identified by the mark ● in the diagram.

It will be observed that when the systems swing in vacuo, the plotted readings are on two straight converging lines. It will presently be shown that when solid friction alone has to be considered its effect on the final reading, i.e. the extent to which it makes the final reading uncertain, is equal to one-quarter of the diminution of amplitude of successive swings. Thus for

Compass *A* angle of uncertainty is about 0·05°.
Compass *B* angle of uncertainty is 0·3°.

Of course, compasses are not tested in this way to determine the angle of uncertainty or error due to solid friction. The method used is described later. It will be seen, from a study of the above curves, that the rapid reduction or damping of the oscillations caused by air friction and electro-magnetic action is very considerable. In the instance of compass *A* an oscillation of 5° amplitude (10° of swing) would, after one minute (the period was 4·5 seconds), be reduced to 4·3° by solid friction only, but the air friction and electro-magnetic damping reduce the amplitude to a fifth of a degree in less than half a minute. And these forces produce no uncertainty in the readings. If the compass case had been of copper the electro-magnetic damping would have been much greater. By properly shaping the moving system it is possible also to increase the air friction. Indeed during the testing of compasses at the National Physical Laboratory numerous instances were met of marked air damping in ordinary prismatic compasses.

In liquid compasses this damping may be made "aperiodic," so that the system when displaced from its position of equilibrium will not oscillate, but will return in a single movement to its position of rest. When the damping is excessive the time occupied in the return is much greater than the time of a complete swing when the system is only slightly damped. When the system is aperiodic and returns after displacement to its equilibrium position in the minimum time, it is said to be "dead beat" or critically aperiodic. Most liquid compasses are not quite dead beat but make at least one complete swing. If it is desired to determine the period of such a liquid compass difficulties arise. For instance, suppose the system to be displaced 10° and that it swings 2° on the opposite side of the equilibrium position before it comes to rest. The time occupied in swinging from 10° to the equilibrium position is different from that taken from the latter position to a displacement of 2° in the opposite direction. The half-period may be taken as the time occupied in passing from the 10° displacement to that of 2°, but it is

well known that the errors of such a measurement are considerable. If the period is desired it is best to displace the system, say 10°, by a magnetic field due to an electric current. Then switch off the current and note the time $T$ taken by the system to first pass its position of equilibrium, and note the maximum displacement on the opposite side. Then the half period is given by the expression

$$T/\left(1-\frac{a}{180}\right) \text{ where } \cot a=1{\cdot}5\ (\log. d_1—\log. d_2).$$

$d_1$ and $d_2$ are two successive displacements on opposite sides of the equilibrium position.

Smith has given the theory by which it is proved that if an oscillating system is affected by solid friction only, the angle of uncertainty is given by one-quarter of the diminution of amplitude of successive swings.

When there is no solid or fluid friction and no electro-magnetic forces tending to stop the oscillations, the time of swing of the system is given by the equation

$$T=2\pi\sqrt{\frac{I}{M\,H}}$$

where $T$ is the time in seconds of a complete swing, $I$ is the moment of inertia of the system, $M$ is the magnetic moment, and $H$ the horizontal intensity of the earth's magnetic field. In England the value of $H$ may be taken as 0·18 C.G.S. unit. Such a system will oscillate for ever, and the oscillations may be represented by a curve $A\ B\ C$, etc. (Fig. 227).

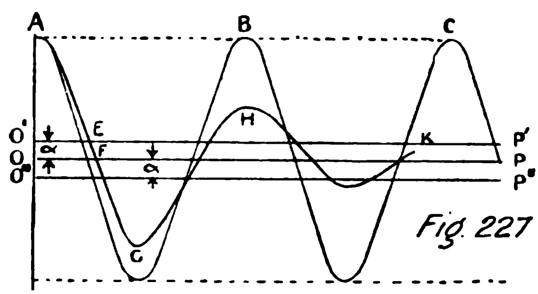



Fig. 227

Let there be now a retarding couple due to solid friction. According to our knowledge this solid friction is independent of the velocity. Let the restoring couple due to solid friction be $D$. When the magnet is displaced through a small angle $\theta$ from its position of equilibrium, the restoring couple due to the action of the earth's magnetic field is $M\ H\ \theta$. The ordinates of Fig. 227 may, therefore, be taken as measures of the amplitude and also of the magnetic restoring couple. The dotted lines $O'P'$ and $O''P''$ are situated at a distance $a$ from $O\ P$, such that $M\ Ha=D$.

When the system moves outwards from $O$ to $A$ the total retarding couple is $M\,H\,\theta+D$, and varies continuously. When moving inwards from $A$ to $E$ the accelerating couple is $M\,H\,\theta-D$, and is a maximum at $A$ and zero at $E$. After passing $E$ the couple changes sign, i.e. $D$ is greater than $M\,H\,\theta$. The passage from $E$ to $F$ is, therefore, dependent on the momentum of the system, and it is apparent that as the oscillations diminish in amplitude the system may come to rest anywhere between the lines $O'P'$ and $O''P''$. The rate of diminution of amplitude is easily found. Thus, when the system moves from $A$ to $G$ the accelerating couple at any point on $A\,G$ at a distance $\theta$ from $O\,P$ is $M\,H\,\theta-D$, the sign of $\theta$ being changed on crossing $O\,P$. This accelerating couple may be written as $M\,H\,(\theta-a)$. If, therefore, we reckon angular displacements from the line $O'P'$ we get symmetry of the curve $A\,G$ about this line. Hence it follows that the part of the curve $A\,E$ is similar to the part $E\,G$. Also the time taken for the system to move from $A$ to $E$ is identical to that taken for it to pass from $E$ to $G$. The decrease in amplitude in the half period is therefore $2a$, and on each complete swing there is a loss in amplitude of $4a$. The form of curve resulting is shown in Fig. 227 (curve $A\,H\,K$).

The angle $a$ is a measure of the frictional error, and is called the angle of uncertainty. If the system be set oscillating the final reading for bearing is uncertain, because of solid friction, by the amount $a$.

It is apparent that if in a prismatic compass there is negligible air friction and negligible electro-magnetic opposing forces, the solid frictional error is readily measured by reading successive amplitudes in the same direction and dividing the difference between them by four. But it has already been shown that in prismatic compasses the fluid frictional force and the electro-magnetic opposing force are by no means negligible, and because of these forces the oscillating system comes to rest much sooner than it otherwise would.

It is evident that in practice the oscillating system will come to rest with an error averaging about $\frac{1}{2}\,a$, and if, therefore, a system is set oscillating a number of times in such a manner that the initial displacements are equal but opposite in direction for successive experiments, the average difference between two successive readings may be taken as a fair measure of the frictional error.

## SECTION V

### Velocity of Projectiles

The highest speeds which have to be measured in practice are those of projectiles. The velocity of a shell of course varies from an initial maximum value attained shortly after leaving the muzzle of the gun to a low value at the end of its flight. The velocity usually measured is the maximum and is of the order of two thousand feet per second, although some of the modern guns are capable of propelling shells at the rate of nearly a mile a second.

The initial velocity of a projectile is an essential factor in ballistic calculations, consequently appropriate methods for determining this velocity have received much study during the past fifty years. The oldest method of determining the velocity is very simple, and consists of two electric circuits fixed at a distance apart. The shell breaks these circuits in succession, and the time interval between the rupture is measured.

Fig 228
Le Boulengé chronograph

The chronograph employed in this work is known as that of Le Boulengé. This chronograph (Fig. 228) is formed of two electro-magnets, joined in series with the batteries and the corresponding wire frames which the shell ruptures. One magnet attracts a tubular bar of the chronometer which terminates at the top in a soft iron point and is enlarged at the bottom; another magnet attracts a rod known as the register. The chronometer is encased in a thin zinc or copper tube. The register is of soft iron, has the same weight as the chronometer, and is pointed at the top and enlarged at the bottom. When the projectile traverses the first frame it interrupts the current of the electro-magnet and the chronometer bar begins to fall freely. When the shell traverses the second frame it interrupts the current of the second electro-magnet and the register then falls and releases a hook which liberates a horizontal spring

pointer, thus immediately striking the falling chronometer bar. The mark on this bar will be the higher the lower the initial velocity of the projectile.

A test is first made in which the chronometer bar and the register fall simultaneously. The height $h$ at which the former is struck corresponds with a time $t$ which must always be allowed for in the subsequent measurement, as it represents the time required by the register to release the spring. According to the well-known laws of dynamics

$$h = \tfrac{1}{2}gt^2$$

$$\text{so that} \quad t = \sqrt{\frac{2h}{g}}$$

in practice when a time $T$ elapses during the passage of the projectile from frame to frame the mark on the chronometer bar corresponds with a time

$$T + t = \sqrt{\frac{2H}{g}}$$

The difference between these two measurements gives the time required : the velocity being given by the formula

$$V = \frac{D}{\sqrt{\frac{2}{g}}\,(\sqrt{H} - \sqrt{h})}$$

The distance $D$ is usually twenty to fifty metres and the time $T$ lies between 0·05 and 0·15 seconds. The chronograph above described is only capable of moderate accuracy, and in recent years has been superseded to some extent by other appliances, such as the Aberdeen chronograph and the Einthoven galvanometer.

*The Aberdeen Chronograph.*—This differs fundamentally from the Boulengé chronograph. It consists of a rotating drum maintained at a constant speed of revolution of an electric motor fitted with a centrifugal governor. Besides giving greater accuracy it has the advantage that the scale is direct reading, so that the velocity of the projectile can be obtained within ten seconds of firing the shell. Instead of wire screens in the path of the projectile, screens of lead foil and paper are employed : the passage of the shot causes electrical connection between the two metallic sheets fixed on either side of a sheet of stout paraffined paper. Each time a screen is ruptured by a projectile the completion of the circuit causes a spark to puncture a record strip on the rotating drum. The chronograph drum consists of a hollow aluminium drum about twenty inches in circumference, mounted on a vertical shaft and rotating at a

constant speed of twenty-five revolutions per second. Within this drum is placed a record strip of prepared wax paper, which is held against the interior circumference by centrifugal force. The record strip is of blue paper coated white on one side with paraffin on which a spark produces a bright blue spot. When the motor is running at normal speed the linear velocity of the rim is forty-one feet per second. The record strip is spun into the drum while the latter is rotating, and is held there very smoothly and firmly due to the centrifugal force. As the projectile in its flight pierces the first screen the circuit of the primary of an induction coil is completed, the secondary sparking through the paper on the drum

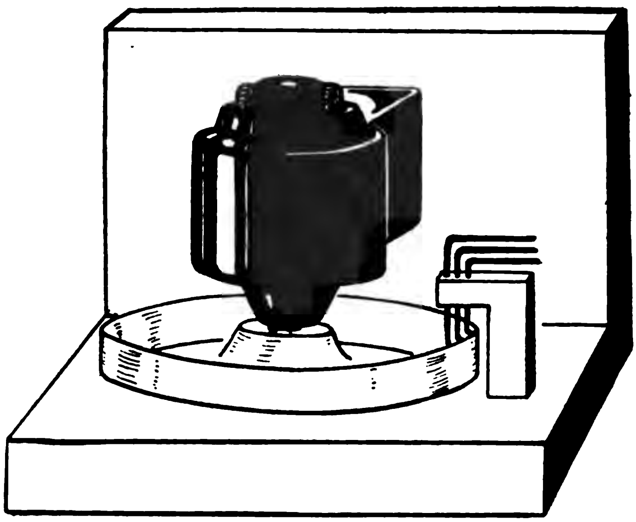


Fig. 229 – Spark chronograph

similarly for each screen in succession. The motor is then stopped and the distance between the two punctures measured, and knowing the speed of the drum the time interval can be calculated.

Tests show that velocities can be measured to an accuracy of 0·34 per cent. The chronograph is calibrated by a ballistic instrument known as the "Fall." This consists of a vertical standard with an electric release permitting a ball to drop a standard distance. For convenience in use it is arranged that the interval is one-fifth of a second, so that there are five revolutions of the drum during the interval and the second spark should be directly under the first one on the strip when running at normal speed. The motor governor consists of a centrifugal device situated on the motor shaft, and rotating with the armature. A weight acting against a coil spring moves with any variation in speed, cutting

in or out resistance in the motor circuit, and thus maintains the normal speed constant within a margin of 0·2 per cent. It will be observed that practically all methods in which minute intervals of time have to be recorded are based on the use of electrical impulses. The inertia of a purely mechanical system of recording is too great to permit of its use, and the problem resolves itself to devising means of rendering successive electrical impulses visible. The sparking method is generally the simplest, but it has the disadvantage of not giving a well-defined mark. If a current indicator is employed it must have an exceedingly short period to ensure that the deflection due to the first impulse has completely died away before the second impulse is received. At the present time two types of galvanometers or current indicators exist which meet these requirements. The Einthoven galvanometer, originally devised by Professor Einthoven, of Leyden, for physiological investigations is a current indicator with a period of about a hundredth of a second. It is essentially of the "moving coil" type, the coil being reduced to a single wire or silvered fibre of about 0·003 mms. diameter stretched in a very narrow air gap between the poles of a powerful electro-magnet. So that when a current is passed along the fibre it is deflected in a direction at right angles to its length and to that of the magnet. The small movement produced is recorded by throwing an enlarged image on to a screen by means of a projector lantern and arc lamp, or on to a photographic plate. The light is directed past the fibre through two holes bored in the pole shoes of the electro-magnet. By the use of silvered glass for the fibre a period of as low as one three-hundredth of a second can be obtained. The tension is so adjusted in practice that the motion is aperiodic, i.e. under an impulse the fibre makes one excursion and returns to zero.

A general view of the instrument is shown in Fig. 230, in which the electro-magnet can be clearly seen, together with the horizontal tubes containing the lens system for projecting light on to the fibre. The fibre is enclosed in the vertical frame between the poles. In recent years the Boulengé method has been largely superseded by the Einthoven galvanometer and recorder for ballastic work and for gun calibration. It is used in conjunction with the usual form of wire screen. A current of a few milliamperes is sent through the circuit in series with the string of the galvanometer, and on rupture of the circuit the galvanometer string returns to zero.

Messrs. F. E. Smith and D. W. Dye have devised a novel method of measuring the velocities of projectiles in which the usual wire or foil screens are replaced by several large coils of insulated wire connected

in series and in circuit with the primary of a transformer, the secondary of which is in circuit with the string of an Einthoven galvanometer. When a projectile passes through the coils a current is induced in the circuit, and this results in a momentary deflection of the galvanometer

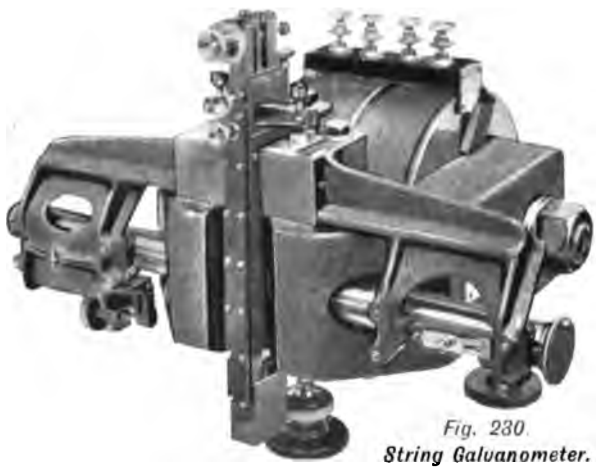


Fig. 230.
String Galvanometer.

string. The photograph of the deflection as obtained on a fast-running cinematograph paper is in the form approximating to that of a complete sine wave (Fig. 231). The coils are set at a distance apart of a hundred feet or so, and the interval of time between the successive surges can be measured to an accuracy of about one fifty-thousandth of a second. A diagrammatic view of the arrangement is given in Fig. 232.

The advantage of the method lies in the fact that no screens have to be replaced after each shot, and the experiment can be repeated as rapidly

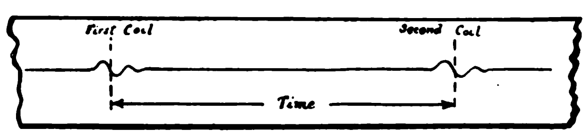



Fig 231

as desired. It is also free from the inherent defect of the wire screen method due to the projectile not always striking the wires at the same point of its length. Time is marked on the tape by means of an electrically driven tuning-fork having a frequency of one thousand per second.

Another specialised form of moving coil galvanometer possessing an exceedingly short period of vibration is the oscillograph, originally devised by Blondel, in France, the practical details of which were thoroughly worked out by Duddel in this country. The principle of the instrument will be understood from the diagrammatic sketch (Fig. 233).

In the narrow gap between the poles $N$ $S$ of a powerful magnet are stretched two parallel conductors $s$ $s$ formed by bending a thin strip of phosphor bronze back on itself over an ivory pulley $P$. A spiral spring attached to this pulley serves to keep a uniform tension on the strips, and a guide piece $L$ limits the length of the vibrating portion to the part actually in the magnetic field.

A small mirror $M$ bridges across the two strips as shown in Fig. 233. The effect of passing a current through such a "vibrator" is to cause one of the strips to advance whilst the other recedes, and the mirror is thus turned about a vertical axis.

In the Duddell oscillograph each strip of the loop passes through a

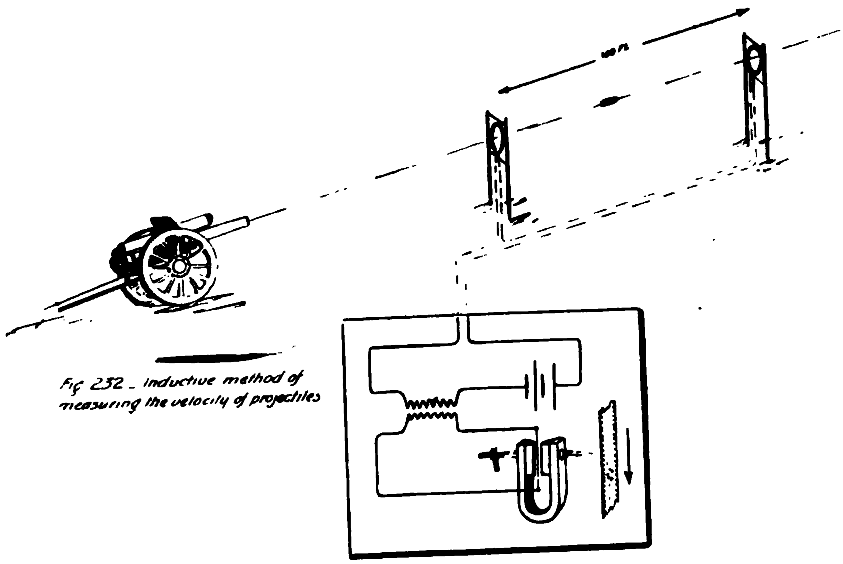


Fig 232 - Inductive method of measuring the velocity of projectiles

separate gap (not shown in the figure). The whole of the "vibrator," as this part of the instrument is called, is immersed in an oil-bath, the object of the oil being to damp the movement of the strips and make the instrument dead-beat. It also has the additional advantage of increasing by refraction the movement of the spot of light reflected from the vibrating mirrors.

The beam of light reflected from the mirror $M$ is received on a screen or photographic plate, the instantaneous value of the current being proportional to the linear displacement of the spot of light so formed. With alternating currents the spot of light oscillates to and fro as the current varies and would thus trace a straight line. To obtain an image of the wave form, it is necessary to traverse the photographic plate or

film in a direction at right angles to the direction of the movement of the spot of light.

The period of an oscillograph can be made very high by increasing the tension on the strips and instruments with a natural period of vibration of only one ten-thousandth of a second have been constructed. They are considerably less sensitive as current indicators than the Einthoven type instruments, and consequently cannot be used in experiments where only minute impulses are obtainable, as in the last-described method.

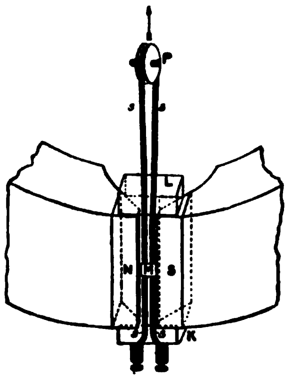


Fig. 233—Principle of oscillograph

The instantaneous response of the instrument to variation of the electric current passing through the strip is well illustrated by the curve below (Fig. 234), obtained by connecting the oscillograph in circuit with an electric lamp. It shows the rush of current through the filament of the lamp at the instant of switching on, owing to the low resistance of the filament when cold compared with the resistance when incandescent.

The rapid decrease in the current during the first hundredth of a second due to the heating up of the wire is very striking. The curve was obtained by Mr. J. T. Morris for a "Just Wolfram" lamp.

Recently Messrs. Curtis and Duncan have employed the oscillograph for recording the motion of a gun during the period of discharging a shell. They arranged a system of contacts with a resistance connected

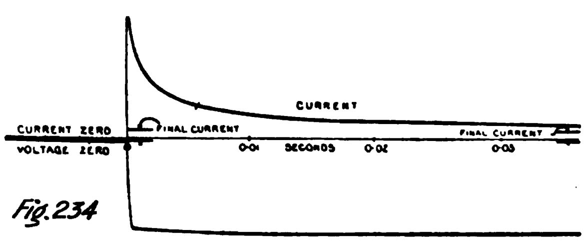



Fig. 234

between each of them. A battery was connected in series with the oscillograph element, the sliding contactor, and this series of contacts. The motion of the gun caused the sliding contactor to move along the series of contacts, thus changing the current step by step in the oscillograph circuit. The apparatus was calibrated in advance, so that the amount of motion required to produce a certain definite step in the current value was known. As the timing lines were ruled on the same

film, this record furnished sufficient data to a distance-time curve of the motion of the gun during the firing of a shell. For timing they arranged a system whereby flashes of light fell across the film at regular intervals, thus ruling it in time units. These units could be made either one-hundredth or one-thousandth of a second.

## REFERENCES

Stanton. "Pitot Tubes, etc.", *Proc. Inst. Civil Engineers*, Vol. CLVI, p. 82. 1903–4.

——. "Vertical Air Current Meter," *ibid.*, p. 7.

——. *Trans. Roy. Soc.*, Vol. CCXIV, p. 199.

——. "Inclined Tube Manometer, 'The Krell,'" *Smithsonian Misc. Coll.*, Vol. LXII, p. 34.

——. *Aviation*, Nov. 1st, 1918.

Pannell. "On the Measurement of Fluid Velocity and Pressure," *Engineering*, p. 261. 1919.

Darwin, Sir H. "Scientific Instruments, their Design and Use in Aeronautics." First Wilbur Wright Memorial Lecture, *Aeronautical Journal*, July, 1913.

——. "Ripograph" (combined set of instruments for flight tests), *Engineering*, p. 845, Dec. 26th, 1913.

Brown, E. B. "The Squirrel Cage Speed Indicator," *The Electrician*, Oct. 26th, Vol. LXXX, p. 117. 1917.

——. "Speed Indicators for Motor Vehicles," *The Automotor Library*, No. 3.

——. "Centrifugal Tachometers on the Principle of the Conical Pendulum," *Zeitschrift des Vereines deutscher Ingenieure*, Nov. 16th and 23rd, 1918.

——. "Tachometer for Airships and Aeroplanes," *Der Motorwagen*, Dec. 10th, 1918.

——. "Air Speed Indicators for Dirigibles," *Jour. of the Frank. Inst.*, Oct., 1919.

Wilke. "Robinson Cup Anemometer," *Zeitschrift fur Flugtechnik und Motorluftschriffahrt*, June 30th, 1917.

Toussaint and Lepere. "Double Venturi," *Bull. de l'Instit. Aerotechnique de l'Univ.*, Paris, Fac. 3, 1913.

Henry. "Appareils et dispositifs Divers Micromanometre," *Journal de Physique*, p. 652. 1913.

Roberts. "On a Compensated Micromanometer," *Proc. Roy. Soc.*, p. 406, 1906.

Baily. "An integrating Anemometer," *Proc. Phy. Soc.*, p. 157. 1882.

Rowse, W. C. "Pitot Tubes for Gas Measurement," *Jour. of Amer. Soc. Mech. Eng.* 1913.

Smith, F. E. "On the Manufacture and Testing of Prismatic Compasses," *Trans. Optical Society.* 1916.

A. Blondel. "Oscillograph," *Comptes Rendus*, 1893, Vol. CXXVI, pp. 502, 748.

Duddell. B. A. Meeting, Toronto, 1897, *Electrician*, Vol. XXXIX, p. 636.

Duddell and Marchant. *J.I.E.E.*, Vol. XXVIII. 1899.

Einthoven. "Ein Newes Galvanometer," *Ann. d. Phy.* 12. 1903.

F. E. Smith and Dye. "Ballistics," *N.P.L. Report*, p. 49. 1919.

Curtis and Duncan. "The Use of the Oscillograph for the Study of Ballistic Problems." Paper read at meeting of American Physical Society, April 25th, 1919. *Abstract Phy. Rev.*, p. 183, Aug., 1919.

——. "A New Chronograph for Measurement of Projectile Velocities and Short Time Intervals (Aberdeen Chronograph)," *Physical Review*, p. 159, Aug., 1919.

J. T. Morris. "On Recording Transitory Phenomena by the Oscillograph," *Proc. I.E.E.*, Vol. XXXVIII, p. 254. *Electrician*, June 7th, 1907.

Duddell. "How to Improve Telephony." Paper, Royal Institution, March, 1906.

Baily and Cleghorne. "Some Phenomena of Commutation," *Proc. I.E.E.*, Vol. XXXVIII.

——. "Notes on the Electro Cardiograph," *Electrician*, April 4th, 1919.

### *Hot Wire Anemometers*

King, Louis V. "On the Convection of Heat from Small Cylinders in a Stream of Fluid: Determination of the Convection Constants of Small Platinum Wires, with Applications to Hot-Wire Anemometry," *Phil Trans. Roy. Soc.*, London, Vol. CCXIVA, pp. 373–432. 1914. Abstract in the *Proc. Roy. Soc. London*, Vol. XCA, pp. 563–670 (II). 1914. *Phil. Mag.*, Vol. XXIX, pp. 556–577, April, 1915. This paper gives full account of the development of subject.

King, Louis Vessot, M.A. "The Linear Hot Wire Anemometer and its Applications in Technical Physics," *Jour. of Franklin Inst.* January, 1916.

Kennelly, A. E. Wright, C. A., and J. S. Van Blyevelt. "Electrical Anemometry," *Trans. A.I.E.E.*, Vol. XXVIII, pp. 363–397. June, 1909

Kennelly, A. E., and Sanborn, H. S. "Electrical Anemometry," *Proc. of Amer. Phil. Soc.*, Vol. VIII, pp. 55–77. April 24th, 1914.

Retschy, C. "The Use of a Hot Wire Anemometer in the Measurement of Non-turbulent Air Currents," *Der Motorwagen*, Vol. XV. March–July, 1912.

Gerdien, H. "A Form of Integrating Hot Wire Anemometer," *Ber. der deutschen phys. Ges.*, Heft XX, 1913.

Morris, J. T. "The Electrical Measurement of Wind Velocity," *The Electrician*, Oct. 4th, 1912, pp. 1056–1059.

——. "Distribution of Wind Velocity about a Circular Rod," *Engineering*, Vol. XCVI, pp. 178–181. Aug. 8th, 1913.

Thomas, J. S. G. "A Directional Hot Wire Anemometer of High Sensitivity, especially applicable to the Investigation of Low Rates of Flow of Gases." *Proc. Phy. Soc.*, 1920. See also *Phil. Mag.*, 1920.

——. "Convection of Heat from Small Wires in Water," *Journ. Frank. Inst.*, p. 115. 1917.

# CHAPTER VI

## MEASUREMENT OF FORCE AND THE COMPARISON OF MASSES

APPLIANCES for the measurement of force are generally known as balances, and one of their most extensive fields of application is in the comparison of masses, which operation is usually referred to as "weighing."

### STANDARD OF MASS

In scientific work the metric system of weights is almost invariably employed, but for engineering work the pound is retained as the unit of mass and force. The merits and defects of this system of units cannot be discussed here, and the reader will find adequate discussion in standard treaties on mechanics.

*British Standard of Mass.*—It is interesting to note that the oldest surviving British standards of weight date from the time of Queen Elizabeth and consist of three distinct sets. The first set are bell-shaped standards of bronze for the heavier weights, and range from 56 lb. to 1 lb. inclusive. From 1588 (the time of their construction) until 1824 they were the standards of the kingdom. The second set is a series of flat circular avoirdupois weights, from 8 lb. to one-sixteenth of an ounce, and the third set a series of cup-shaped troy weights, which, with the exception of the very small weights, fitted into each other. These are based on still older standards.

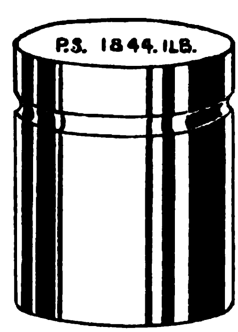



Fig. 235
British Standard
Pound

In 1844 a new standard, termed the Imperial Standard Pound, was constructed. This was made of platinum, 1·35 inches high, 1·15 inches in diameter, and of a density of 21·1572. It has a slight groove near its upper surface by which it may be moved with an ivory fork. Fig. 235 represents a full-size view of the standard, which bears on its upper surface "P.S. 1844, 1 lb.": the letters

being an abbreviation for "Parliamentary Standard." It is, of course, the primary standard of this country at the present day, and its value is accurately known in terms of the International Kilogram.

## SECTION I

### Balances

Balances may be broadly divided into three types :—

I. The Suspended Pan Balance, which in its equal-arm form is used for all precision weighing, and to some extent for light commercial work.

II. Spring Balances employed for domestic purposes, and sometimes in engineering work, for the measurement of force.

III. Platform Balances.

*The Equal-arm Balance.*—The equal-arm balance is universally adopted for scientific and analytical work on account of its great sensitivity and accuracy. This system of levers has the minimum number of parts and centres, consequently the least possible sources of error. With a well-made balance it is possible to weigh a load of one thousand grams to one milligram—an accuracy of one in a million, which certainly cannot be attained with the same ease in the case of the majority of other physical measurements.

The elements of a precision balance are well known and need no detailed description.

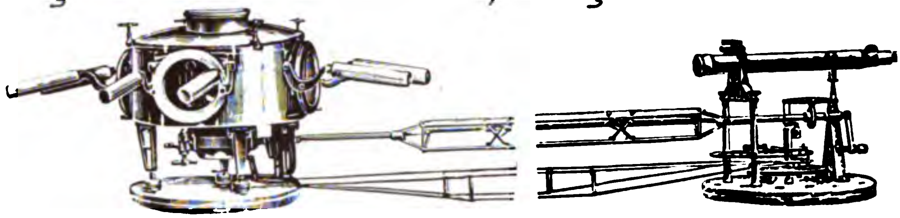
Before passing on to an account of the modern appliances employed for accurate weighing in technical practice, a brief description will be given of the balances which have been developed for work demanding the highest possible precision, namely, the comparision of national standards of mass. This work is carried out at the International Bureau of Standards and Weights located at Sèvres, near Paris. The Bureau is maintained from subscription made by the various countries in the convention.

*Precision Balance for Verification of Fundamental Normal Weights.*—For this comparison work of the ultimate standards with their copies, the balances employed are designed especially for the comparisons of very nearly equal masses. Such balances necessarily embody all the refinements which experience and scientific knowledge can suggest. The International Bureau possesses, for this work, probably two of the best balances that have yet been constructed.

It was proved by Jolly and Crookes, half a century ago, that the greatest source of difficulty in precision weighing was the variations of

temperature and humidity of the air in the balance case. This renders the correction for air displacement somewhat uncertain; besides, non-uniformity of temperature causes unequal expansion of the arms of the beam, and sets up convection currents. Hence a balance was constructed which could be operated in vacuo.

Fig.-236 Vacuum balance with operating mechanism



*The Vacuum Balance.*—The balance was constructed by Bunge, and is so arranged that all the adjustments can be made from outside. Moreover the control gear is at a distance of several metres from the balance to avoid temperature changes due to the presence of the observers.

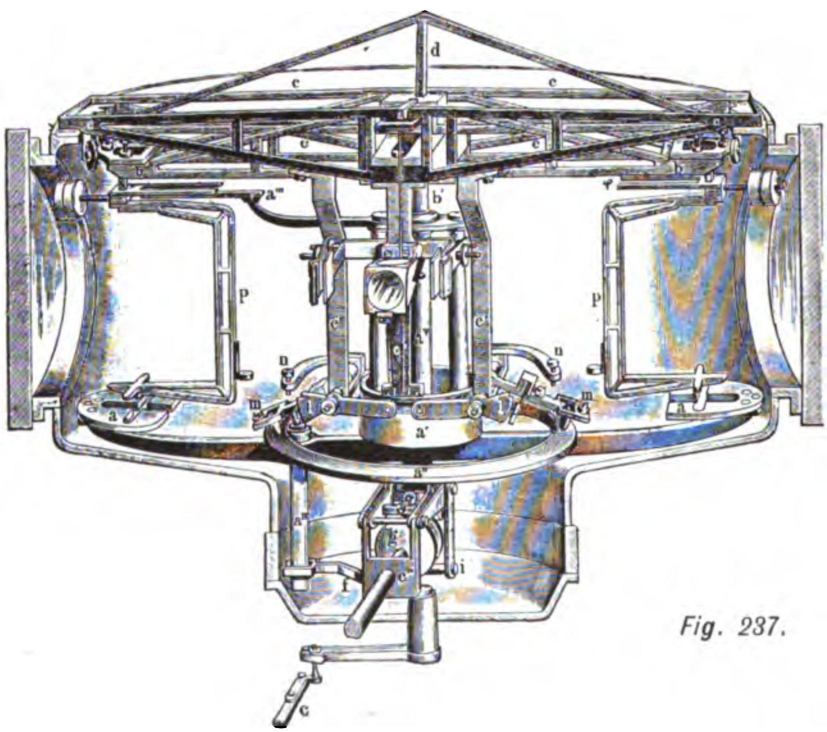


Fig. 237.

Fig. 236 shows the external arrangement of the balance and control pillar, while Fig. 237 is a sectional view showing the various parts of the mechanism. The beam *d* swings on agate tables in the rigid frame *c*,

which frame also projects downwards in $c^{I}$ $e^{I}$ to carry the lower part of the structure. The relieving gear $b$ has a vertical movement through the tube $b$ from the cams $g$ at the base, and is guided by rollers at its ends bearing on vertical rails inside the case. The relieving frame takes the weight of the hangers $p$ off the knife edges as well as lifting the beam. The weights under comparison are placed in position and interchanged for double weighing by a "transporter," $a$ rotating about a tube $a$.

This arrangement has a vertical and rotating movement from $g$ and $f$ respectively. The vertical movement lifts the arms $a$, which are cut away to allow the pan supports to pass through them. The plates $a$ lift the two kilogram weights, and rise sufficiently high to pass over the pan supports when the "transporter" has to be rotated. The weights can then be carried around through 180 degrees and deposited on the pan supports in the alternative position. The pan hangers have complete freedom to swing by the use of three sets of knife edges.[1]

Provision is made for arresting the oscillation, this mechanism being in the form of two small arms $m$ bearing on a ring $a^{II}$ on the transporter. The vertical motion of the transporter causes a small cone on $m$ to rise into contact with a cup on $p$, thus damping out any swinging motion. The levers are so arranged that the point $m$ is depressed out of contact with the cup just before the weight is placed on the pan arm. The transporter gear serves the additional function of placing in position and interchanging the small weights necessary for counterpoise. For this purpose the upper end of the tube $a^{V}$ carries an arm $a^{III}$, this arm rotates around the axis and can take up, by virtue of the vertical motion it shares with the transporter, any one of a series of small weights in a rack (see Fig. 237) at the back of the case. These weights can be deposited in the U-shaped projections at the top of the pan hanger $p$. The operation of the arm $a^{III}$ is arranged to take place with only a partial lift of the transporter, so that the main weights on the pan arms are not disturbed. The deflection of the beam is observed optically by the use of a mirror and prism in the usual way. The curious arrangement of balance weights for keeping the cover glasses down on the windows will be understood from a study of Fig. 236.

The other balance, also capable of being operated from a distance, is shown in Fig. 238. This was designed for ordinary comparison work, in which the highest attainable order of accuracy was not desired. Readings are taken by means of a telescope and scale from a distance of

[1] Some particulars concerning the compensated pan suspensions will be found on page 233.

three to four metres, but balances of a similar type have been made without the transmitting gear.

On examination of Fig. 238 it will be observed that a horizontal mirror is attached to the beam of the balance, the light rays being reflected to and from it by another fixed mirror just above, set at an angle of forty-five degrees. The weights are interchanged in the two pans by

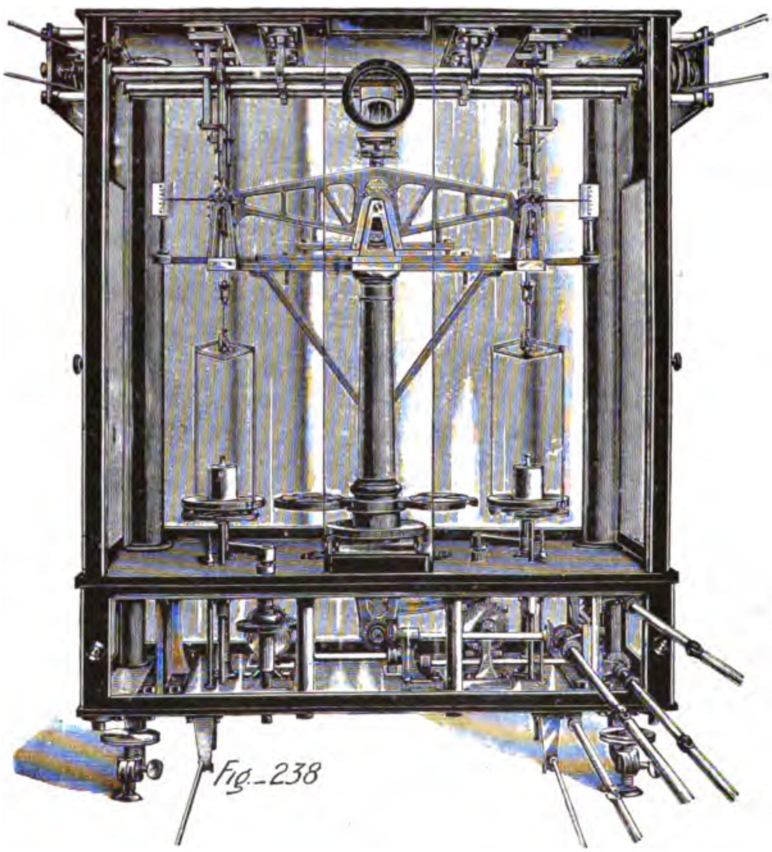
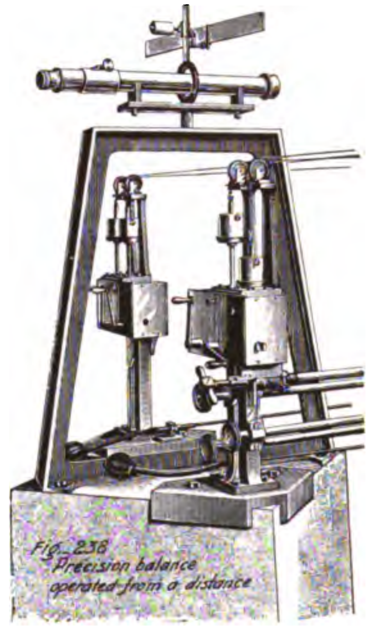


Fig. 238

an automatic device operated by levers different from the one previously described. In the first movement each weight is lifted off its pan, they are then placed on the adjacent platforms attached to the vertical pillar, these rotate about the pillar, and in the next operation the weights are transferred on to the scale pans. The small weights required to produce exact equilibrium can also be applied from a distance and automatically register themselves on the scale of a separate apparatus fixed in the balance. Balance operation from a distance is not favoured in routine

work even when precision weighing has to be done, owing to the costly and cumbersome gear that it involves.

The Bureau discovered another minor disadvantage of the system on one occasion, for it is related that the balance (Fig. 238) behaved in a most erratic manner during the course of some comparisons. Careful examination of the balance at close quarters proved that the disturbances were due to the presence of a minute insect promenading along the beam!




*Disturbances due to Temperature Fluctuations.*—As already stated, one of the greatest practical difficulties encountered in accurate weighing is the influence of temperature fluctuations. The expedient of evacuating the case cannot be employed for ordinary work, but experiments have shown that a very substantial improvement in the steadiness of a balance can be effected by enclosing it in a metallic case with a perforated base to allow the suspension wires of the pan to swing freely. The author has not been able to trace the origin of this idea, but it is recorded that a balance of this type was constructed in 1895 for the Russian chemist Mendeleef, by Oertling. A modern form of protected beam balance is shown in Fig. 239. The balance is fitted with a double front slide, and the beam is protected with a mahogany base covered with magnalium or copper. In some balances baffle-plates are secured to the pan suspension wires and pointer immediately

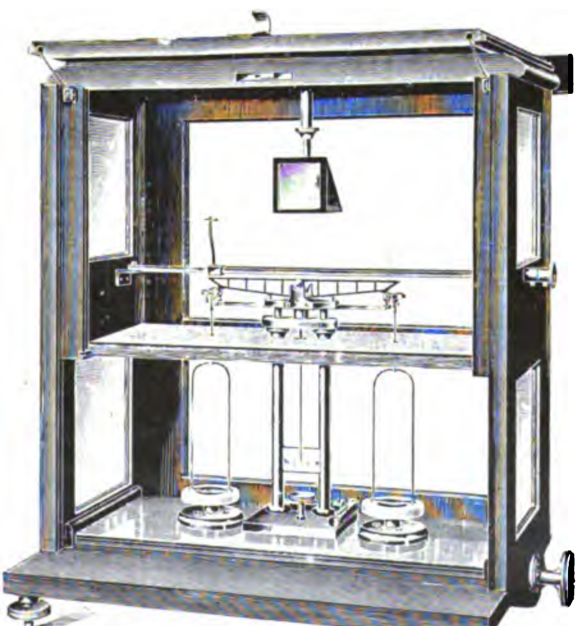
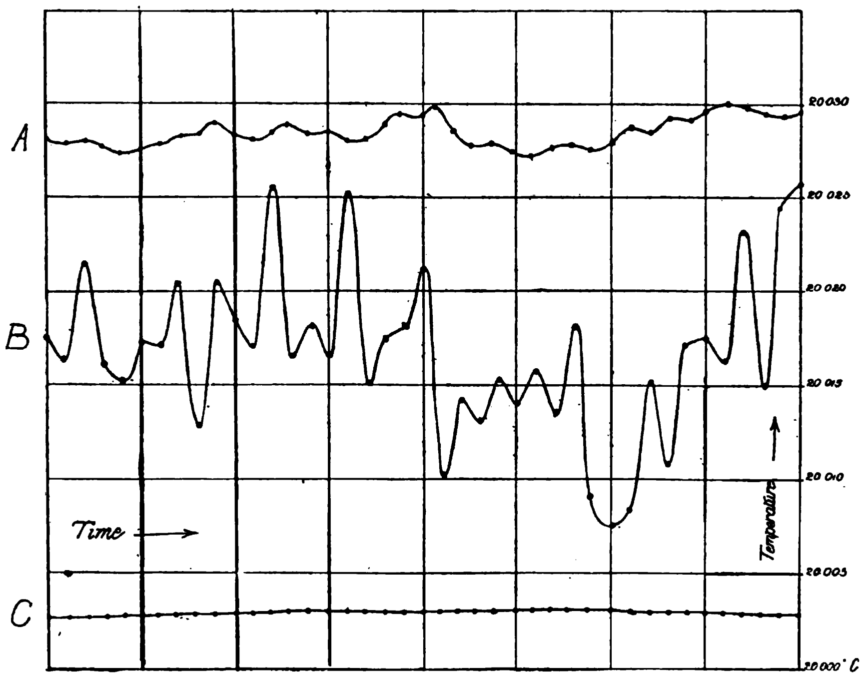


*Fig. 239.*—Balance fitted with internal partition to protect the beam.

below the base-plate of the inner case. These baffle-plates intercept and deflect any convection currents from the operator's hand, and so prevent them from obtaining access to the beam through the openings in the base-plate.

Manley has published some data on the variations in temperature within a balance case in the neighbourhood of the beam. The temperature was measured by means of a large resistance thermometer so dis-

Fig. 240 Temperature fluctuations in balance case under various conditions




posed as to give the mean temperature. The order of the variations can be seen from a study of diagram (Fig. 240), the ordinate scale of which is $\frac{1}{200}$° C. per division. Curve *A* represents the oscillation when not in use; Curve *B* the violent oscillation of temperature caused by the presence of the observer loading and unloading the pans, both curves referring to an unprotected beam. Curve *C* was obtained with a protected beam during loading and unloading, and the improvement effected is marked. An additional advantage of the protecting case is that it protects the beam from dust.

*Factors Governing the Sensitivity of a Balance.*—It can be shown by

a consideration of the statics of the problem that the sensitivity $S$ of a balance is given by the equation :

$$S=\frac{l}{Wh^1+w^1(h+h^1)} \text{——}(1)$$

$$S=\text{sensitivity, is defined as the ratio } \frac{\theta}{dw}$$

Where $\theta$ =deflection, $dw$=increment of weight added.

And $l$=length of the beam,

$W$=total load on both knife-edges, including pans,

$w^1$=weight of beam,

$h$=distance of centre of gravity of beam below plane of the end knife-edges,

$h^1$=distance of central knife-edge above the plane of end knife-edges.

It will be observed that the sensitivity decreases if $h^1$ is appreciable. The period of vibration of the beam can be expressed as

$$T=2\pi\sqrt{\frac{wl^2+w^1K^2}{gw^1h}} \text{——}(2)$$

Where $K$=radius of gyration of the beam about the central knife-edge,

$g$=acceleration due to gravity.

The above equations indicate the two incompatible conditions which confront the designer of a balance. High sensitivity is obtained by making the beam long, while, on the other hand, a quick period for rapid weighing requires the beam to be short and its radius of gyration small. There is a tendency to obtain the required sensitivity by greater magnification of the deflection and to keep the beam short. The short beam has the advantage of reducing the radius of gyration, the weight of the beam and increasing the stiffness, thus tending to maintain the knife-edges co-linear.

*The Balance Beam : its Design and Adjustment.*—The beam is the principal element in all appliances designed for the measurement of force or the comparison of masses. Hence its design and construction merits careful study, since it is often the limiting factor in fixing the accuracy attainable in the measurements. In practically all balances for scientific work the arms of the beam are made equal to facilitate verification of the adjustment by merely interchanging the loads in the two pans. A typical form of heavy beam is shown in Fig. 238. This is constructed in the form of a triangle so as to obtain the minimum mass. The design of the beam varies considerably according to the predilection of the manu-

facturer. Some modern designs are shown in Figs. 241, 242, and 243. In the form shown in Fig. 241 an endeavour is made to utilise the rider bar as a structural element in the beam. Fig. 243 illustrates a balance beam constructed of a double triangulated plate of aluminum alloy. This gives great

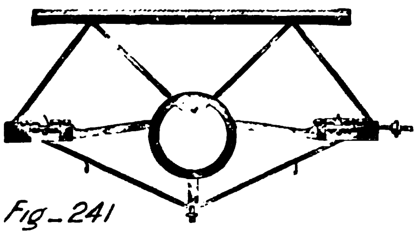


Fig. 241

load-carrying capacity without distortion. In all cases the central or main knife-edge is designed to carry the load distributed along its entire length.

These beams are made of cast metal, and it is important in the manufacture that a thick layer of the surface should be machined away to eliminate casting strains and distortion. Bunge, of Hamburg, endeavoured to overcome the inherent trouble due to casting strains by constructing a beam entirely from copper-nickel alloy rods and sheet metal. This mode of construction has the incidental advantage of making the coplanar adjustment of the knife-edges a very simple matter by merely shortening or lengthening one or other of the rods constituting the structure.

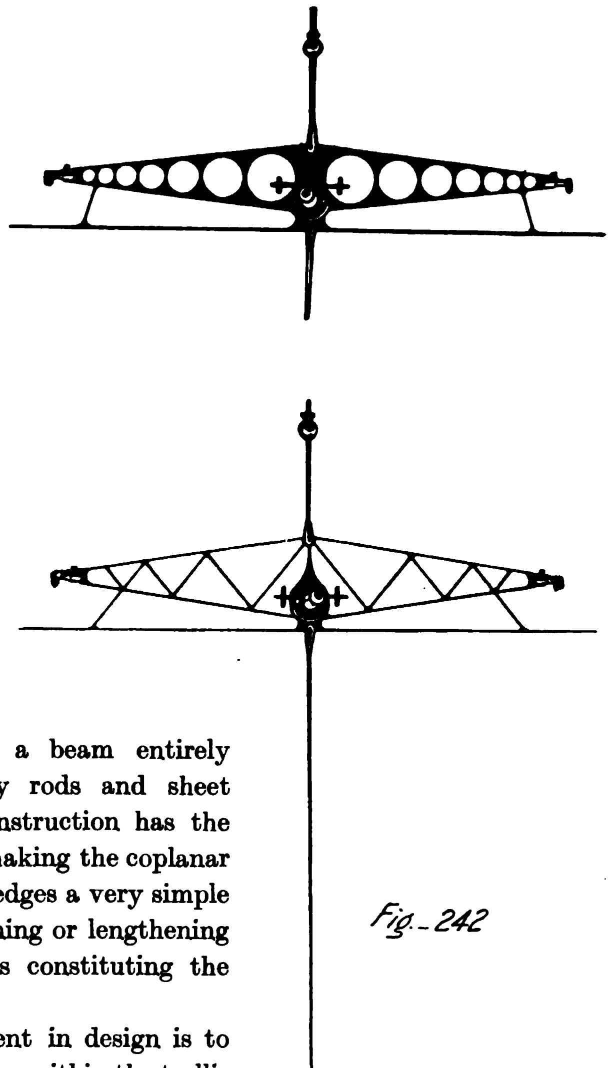


Fig. 242

A modern improvement in design is to arrange the end knife-edges within the trellis work, as it has been found that if the knife-edges are attached to short extensions of the beam outside the trellis configuration there is a marked flexure in these extensions. This results in a variable sensitivity

due to the lowering of the end knife-edges. This defect is avoided in the design of beam shown in Fig. 241, in which it will be observed the end knife-edges are fixed within the triangular structure.

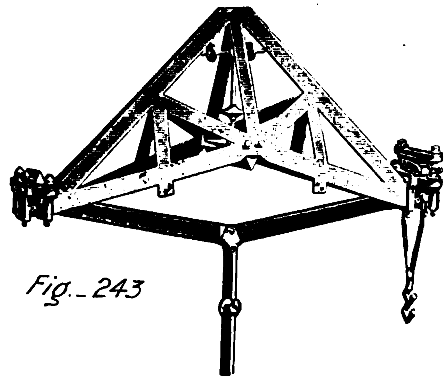


Fig. 243

*Material for the Construction of the Beam.*—The chief requirements in the properties of the material for making a balance beam are rigidity, non-oxidisability, and low specific gravity. Brass is now replaced to a large extent by the well-known aluminum alloy magnalium, consisting of 86 per cent aluminum, 13 per cent magnesium, with silicon iron and copper as impurities. For trade balances iron is almost exclusively used, and there is not much advantage in making the beams of trellis form, since ample sensitivity for the purpose is obtainable with the cheaper construction.

When a beam is made of oxidisable metal it is, of course, necessary to protect it, and at one time a coating of lacquer was universally used. Warburg and Ihmori condemn the use of lacquer owing to its hygroscopic properties. The alternative is gilding, and this has to be done with great care, since the presence of traces of cyanide salt in the pores and interstices leads to the formation of alkali carbonate, resulting in fissures. Moreover, the salt produced is strongly hygroscopic. Nickel plating or platinising seems to be the most stable covering.

*Adjustment of Steel Knife-edges by Grinding.*—Cheaper balances have their knife-edges, usually of steel, dove-tailed into the beam. The methods employed for adjusting such knife-edges vary with different manufactures and is usually effected by distorting the beam by hammering. The grinding method devised by Hasemaun, twenty-five years ago, has the merit of being based on sound mechanical principles, so a brief description of it may be of interest.

The central knife is ground true and finished before insertion, while the end knife-edges are ground in position as follows :

The beam is set in a jig (Fig. 244) consisting of an accurate plane surface $D$ and the facing $E$. The inner face of the knife-edge $E$ is then ground by the rotating grinding disc $F$, whose plane is accurately parallel to the line of intersection of $E$ and $A$. Hence the ground face is parallel to that of the central knife-edge. The beam is then turned length-wise,

about an horizontal axis, to the position indicated by the dotted knife-edges. The outer surface of the knife-edge $B$ is then caught by the upper surface of the grinding disc $F$. Since the grinding surfaces of the disc $F$ are separated by the thickness of the wheel for the new position, the beam must be moved up or down, or laterally, to make room for the

Grinding jig for adjustment of steel knife edges

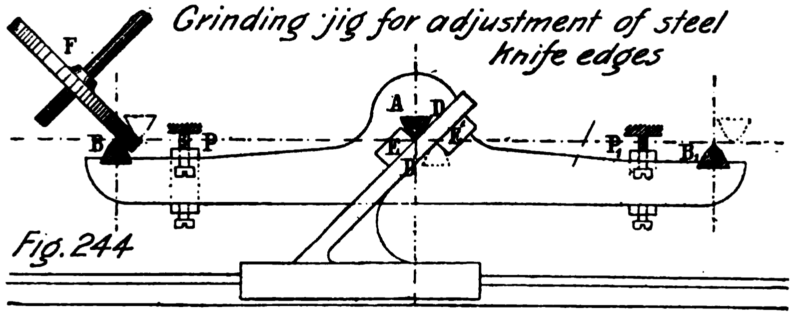



Fig. 244

grinding disc between the two positions. Hence a second vee is provided for the central knife-edge, against which it is held from below and indicated by $D^1$ $E^1$ in Fig. 244.

The second ground face on the knife-edge $B$ will obviously be also parallel with the central knife-edge, so the line of intersection of both, i.e. the knife-edge will be parallel with the central axes. Similarly the knife-edge $B$ is ground parallel to the central axes. A further condition which has to be complied with is that the knife-edges $B$ and $B_1$ be equidistant from $A$ and lie in the same plane as $A$. Both these requirements are met by fixing accurately adjusted stops $P_1$ $P_1$ so that after the completion of each grinding operation any one of the planes of the balance beam becomes exactly parallel to its original position. The stops prevent further grinding when the normal position is reached. By a slight modification and elaboration of the method it is possible to arrange a jig such that the beam is always laid in the bed from above.

*Knife-edges.*—The knife-edges of accurate balances are always made of agate or rock crystal, on account of the necessity for a hard, non-rusting surface. The use of these materials has the incidental disadvantage of liability to chip, and, moreover, agate appears to be strongly hygroscopic. Means of adjusting the end knife-edges to obtain equal arm length and parallelism of the three knife-edges are usually provided. Although in the cheaper types of chemical balances the knife-edges are fastened in triangular blocks of steel, dovetailed in, as shown in Fig. 245, and consequently no fine adjustment is possible.

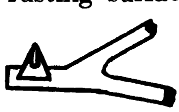


Fig. 245

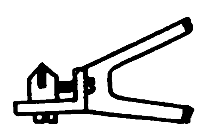


Fig. 246

A better method of attachment is shown in Fig. 246. Here the knife-edge block is held down by a screw passing through a slotted hole, and traverse motion is obtained by the aid of the screw bearing against the side of the block. For the best class of balances more elaborate methods of attachment are employed. Two forms used by Sartorius are shown in Fig. 247, A and B.

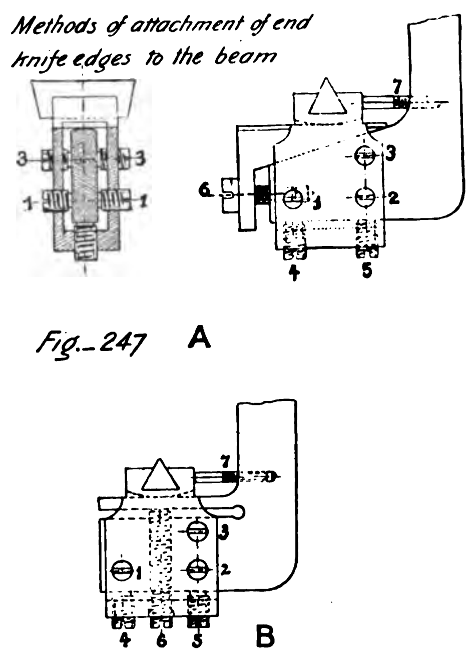



Fig._247

The agate knife-edge is fixed in a casing, which is pushed into position on the end of the beam. The casing rests either as shown in type A with a cylindrical arch upon a wedge, or upon a plate or face-spring, in type B. Through the sides and bottom of the casing are tapped five screws, so that the screws 1, 2 lie in an horizontal and the screws 2, 3 in a vertical plane. Just according as to whether one is working with each set of screws the knife-edge is turned about vertically or horizontally. The correct position of height, according to type A, is attained through the wedge by means of the screw 6, whilst the first adjustment, that of arm length, is attained through 7. For the accurate setting of the equality of arms the screws 4 and 5 are used ; through these a turn of the knife-edge about the middle point of the cylindrical arch can be effected. In type B the correct position in height of the knife-edge is attained by moving the pressure screw 6, which presses against the spring face, as also by the screws 5 and 4. The task of adjustment is exceedingly laborious. Only by numerous weighings can existing errors be detected and rectified, and it is assumed that only slight adjustment is necessary, since the methods of construction employed ensure, in the first instance, a reasonable degree of accuracy.

Walker states that the following procedure is employed by the makers :—

The central knife-edge is first set at right angles to the plane of the beam, by means of a square ; the three knife-edges are now adjusted to be in the same plane by means of a carefully made straight metal bed,

The beam is rested on this by its central knife-edge, and one of the terminal knife-edges having been brought to the level of the bed by a straight-edge placed along it, the other knife-edge is then adjusted till it is in this plane: this is tested by placing a second straight-edge across the bed over first one end and then over the other end of the knife-edge. This adjusted knife-edge is then used in the same way for adjusting the first to touch the straight-edge along its whole length. Large adjustments have to be made by packing or filing, but the knife-edge can be slightly raised or lowered by tapping with a flat hammer the lower or upper part of the vertical side of the beam near the knife-edge. The arms are then made equal and the knife-edges are set parallel by direct measurement, the final adjustment for the equality of the arms being made with the balance itself. It is a most important matter to test whether the adjustments made in this way are free from errors which can be detected by the use of the balance. The first test is for the parallelism of the knife-edges: an error in this may occur in two ways, either in a horizontal or in a vertical direction, causing respectively a change in the position of equilibrium and in the sensitivity when there is a shift of the point, in which the vertical through the centre of mass of the pan and its contents cuts the knife-edge. To test for the first of these errors a mass $P$ is suspended from one end of the knife-edge and counterpoised by a mass suspended in the other pan: $P$ is then shifted to the other end of the knife-edge; any change in the position of the equilibrium will indicate that that end of the knife-edge at which $P$ appears lightest is nearest the vertical plane through the central knife-edge.

The error in the vertical plane is tested for in a similar manner: the sensitivity is determined when the mass $P$ is in the two positions, and that end will be lowest at which the sensitivity is least. The accuracy of the positions of the knife-edges is next tested: to test whether the three knife-edges are in the same plane the sensitivity of the balance is determined for different loads; if this remains constant the adjustment is correct. Only in the highest class of balances, such as the Bunge and Sartorius, are means provided for altering this adjustment, but in cases in which adjustment is possible the procedure is as follows:

The beam is poised without the pans and the position of equilibrium noted: the sensitivity corresponding to the same position of equilibrium is determined when a mass $P$ is suspended from the knife-edge $A$: the masses suspended from the knife-edges are then doubled and the gravity bob adjusted until the sensitivity is the same as in the former case: the bob is moved back through double the distance moved and the knife-

edge $A$ then adjusted until the same sensitivity is obtained. It is assumed, of course, that the gravity bob moves in a vertical direction. The correctness of this method may be proved by working out the statics of the problem.

The equality of the arms of the balance is shown by there being no change in the position of equilibrium when equal masses are placed in the pans : if they are unequal, one knife-edge must be adjusted till this condition is satisfied.

*Method of Pan Suspension from Beam.*—Theoretically the three knife-edges of a balance should be perfectly parallel and the two end ones in the same plane. These conditions can only be approximately realised in practice in spite of all the adjusting contrivances on the knife-edge carriers. It is, of course, obvious that for most purposes the accuracy obtainable with such adjustments will be sufficient, but in the balances of the highest precision it is usual to provide means of compensating out the small residual errors. Hence it is definitely assumed that the knife-edges are warped in both the horizontal and the vertical plane. The consequence of such warping is that the beam is of an indefinite length, varying according to the point at which the resultant of the load on the pan intersects the knife-edge. So it is necessary to insert in the pan suspension a joint which ensures that the load is always applied to the knife-edge in exactly the same line whatever may be its position in the scale pan. The arrangement of plan and knife-edges to satisfy this is shown diagrammatically in Fig. 248.

On the end knife-edge $X$ $X$ rests a plane surface which carries a framework. The framework rests on the top of the plane surface along the axis $Y$ $Y$ at right angles to $X$ $X$. The pan is supported on the knife-edge $Z$ $Z$ parallel to $X$ $X$ and perpendicular to $Y$ $Y$.

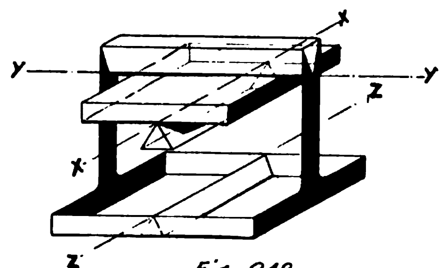



Fig. 248
Diagrammatic sketch of compensated pan suspension

It will be observed that freedom in two planes is obtained by the axes $X$ $X$ and $Y$ $Y$, and it would appear as if the axis $Z$ $Z$ were redundant. It is, however, essential, since the knife-edge $X$ $X$ cannot be regarded as a line of no width, but rather as a cylinder of small radius. Any rolling of the table on this cylinder would necessarily alter the effective length of the balance arm, so this possibility is eliminated by allowing the pan support to roll on $Z$ $Z$.

In the vacuum balance already described (page 221), this device is

incorporated with an inversion in the knife-edge and table *Y Y*, as shown in Fig. 249. Hence, in this balance, there are a total of seven knife-edges, and in addition the precaution is taken of centring the load by repeatedly arresting and lifting the load off the pan by the automatic devices already described.

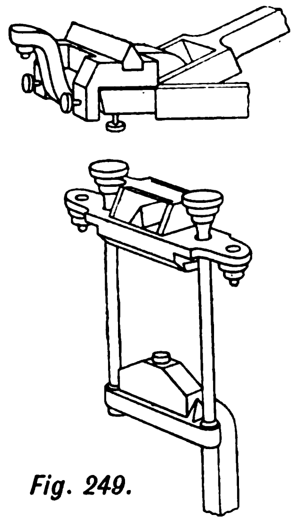


Fig. 249.

*Quick-loading Devices.*—It is a curious fact that in spite of the considerable time absorbed in changing weights during a weighing operation the various devices which have been brought out to expedite the work have met with but limited favour, owing, presumably, to the initial extra cost. One of the earliest devices to facilitate weighing, and the only one which has come into general use was the movable rider which is familiar to every one who has had occasion to use a modern balance. One of the troubles with the early forms of balances so fitted was the frequent loss of the rider when the carrier was brought too quickly up against the stop. This defect has now been largely eliminated by the use of the mechanical contrivance shown in Fig. 250. From a

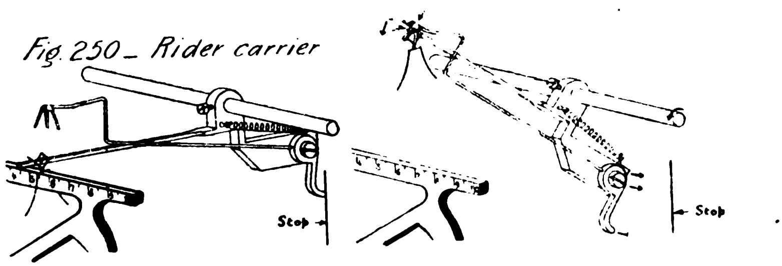



Fig. 250 _ Rider carrier

study of the illustration it will be seen that the forked end of the rod clamps the rider as soon as it is lifted clear of the beam.

Another very simple device for changing the fractional weights is

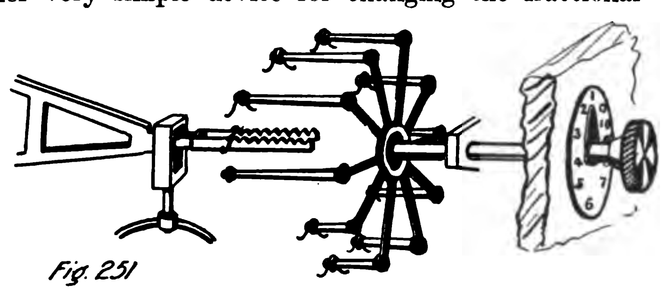


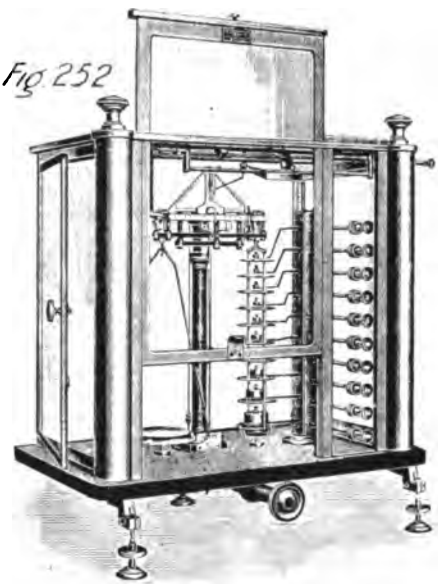
Fig. 251

shown in Fig. 251. Each arm carries a small weight in the form of a bent wire. These weights are of such values that they produce equal

moments about the central knife-edge when lowered into their appropriate notches. The ten arms are of uniformly graduated length, so the weights are deposited in successive notches by the rotation of the arm.

Another device to effect the same result for weights from one gram upwards consists of a special form of balance pan with a series of cups in the form of a vertical tier (see Fig. 252). Rods project in from the side of the case and carry the weights at their ends. When a rod is pushed in the weight is placed over the appropriate cup and the balance pan when released takes the load. The cups are slotted out to clear the arm. With this system subdivisions of the gram are obtained by the use of a rider arm in the usual manner.

Fig 252



In the Heusser Balance the weight-changing mechanism represents the lever motion seen on typewriters, and the balance has been developed with the special object of facilitating the weighings necessary in analytical work. A general view of the balance is shown in Fig. 253, while Fig. 254 illustrates the weight-changing mechanism in greater detail. The pan-hanger on the right carries a perforated plate or grid. Behind this pan-hanger a short column is solidly mounted on the base-plate carrying nine movable levers. The front end of each of these levers carries an upright conically-tipped staff which moves centrally and vertically through the perforations of the grid. The levers are operated from the outside by means of depressible push-keys, and located in front of the balance. Illustration shows seven levers in their uppermost position with the weight at rest and two levers in their lowermost position with the weights deposited upon the grid. The weights are in the form of discs, each disc having a central perforation. At rest they are supported by means of the conically tipped staffs which extend partly into the perforations; when in use they are deposited in counter-sunk holes in the grid. These weights may be deposited and again picked up independently of each other and while the balance beam is free to swing by simply pushing the depressible keys up and down. The value of each weight is marked upon an index plate placed above the keyboard. The capacity of the

weights is 221 milligrams for Assay Balances, and divided as follows : 1, 2, 3, 5, 20, 30, 50 and 100 milligrams. For extremely delicate weighings, where the $\frac{1}{2}$ milligram rider is used, the capacity is only 121 milligrams, and for Analytical Balances the weights are ten times heavier, or 2220 milligrams in all.

Another novel feature of this balance is the mechanical pan extractor seen on the left-hand pan in Fig. 253, which enables the operator to set

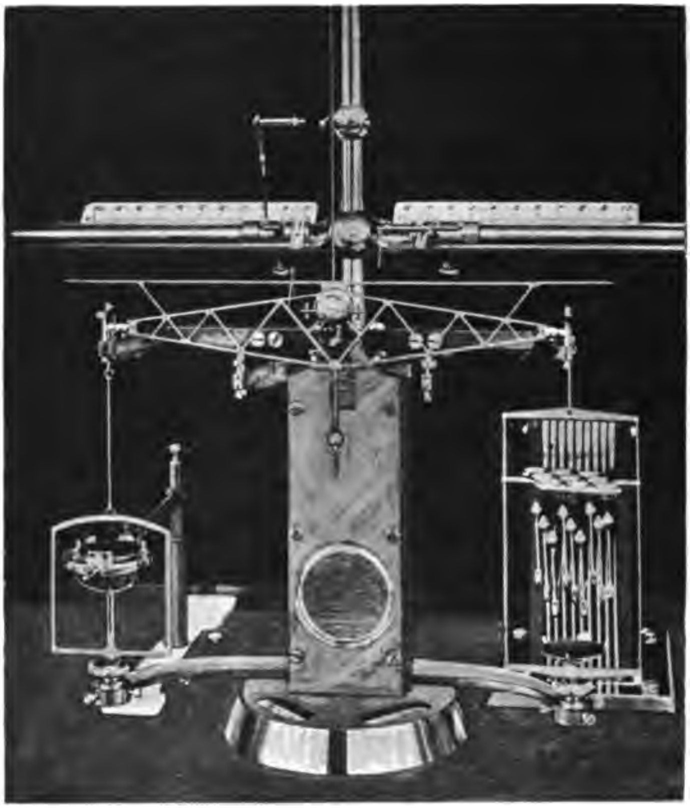


*Fig. 253.—The Heusser Balance.*

the assay " button " on the pan and get it out again without opening the balance door. The balance pan is supported in the centre of the hanger frame. Behind this frame a vertical post protrudes from underneath the balance sub-base. This post is actuated through the knob located in front of the balance and has an alternative vertical and horizontal motion. At the top of this post is clamped a horizontal arm, which reaches forward into the hanger frame. The forward end of this horizontal arm has three centrally projecting prongs, into which the

balance pan fits. A round hole, 1¼ inch diameter, is drilled into the glass panel of the balance door, through which the pan is brought outside of the balance casing. This hole is covered by a glass shutter, which is automatically opened and closed through the operation of the front knob.

*Operation.*—When the vertical post with the horizontal arm is in its lowermost position, then the balance pan has been placed upon the

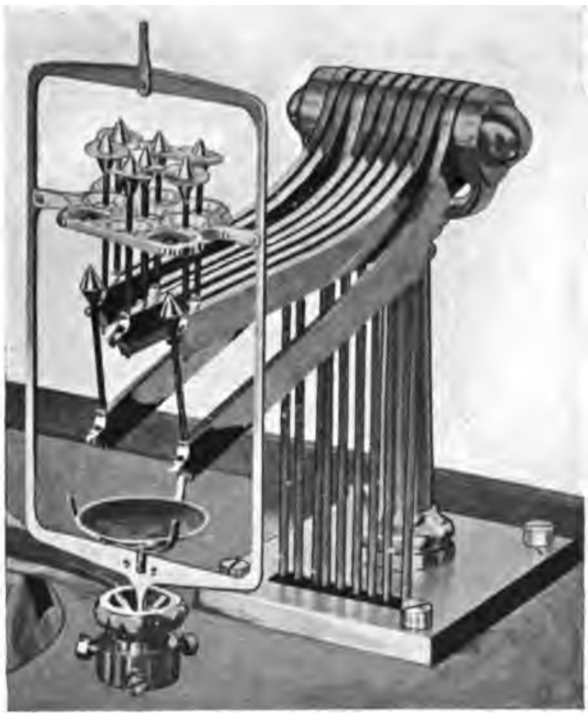


*Fig. 264.—Detail of the multiple weight attachment.*

In the configuration shown two of the keys outside the balance-case have been depressed, and the corresponding weights are deposited on the grid.

hanger and the balance is ready for operation. In order to extract the pan, the knob in front is turned one-half turn in a clock-wise direction, which brings the post with the arm and the pan back into their uppermost position. Pulling the knob forward opens the shutter automatically and brings the pan outside of the casing. In order to replace the pan upon the hanger the order of all motions is reversed. The knob is pushed back to the stop which allows the shutter to close automatically. Turning the knob in the counter clockwise direction places the pan again upon

the hanger. All motions are limited by stops. The possibility of upsetting the pan and hanger through false movement is eliminated by means of automatic locking devices. The door may of course be raised or lowered in the same manner as in an ordinary balance, provided that the pan extractor is pushed back.

## Novel Types of Balances for Special Purposes.

The preceding types of balances are designed for the routine weighing operations encountered in scientific work. In addition to these there are a number of appliances belonging to the same general category which have been developed to meet special requirements, such as the accurate measurement of the force on aircraft models due to wind velocity; the determination of the specific gravity of gases; the measurement of electric currents; and the weighing microscopic quantities of material.

*Balance for the Measurement of Forces on Models.*—In the development of aeronautics experiments on scale models have proved to be of immense value in settling points of design and in enabling a prediction to be made beforehand of the stability of new types of machines. With the aid of an appropriate form of balance it is possible to measure the various forces on a model placed in a definite wind-stream with considerable exactitude.

Before passing on to a description of the balance it might be remarked that a wind-channel consists essentially of a long rectangular box through which air is drawn at a steady velocity by means of a fan fixed at one end. Uniformity of flow over the greater portion of the cross-section of the channel is obtained by two honeycombs, one at each end; the first being at the mouth and the second in front of the airscrew. For all practical purposes the velocity may be taken as uniform to within six inches of the sides, where it falls off rapidly. The velocity of the wind stream is usually obtained by means of the Pitot tube and tilting gauge described in the last chapter. About midway down the channel the model under test is placed fixed to the vertical arm of the balance, as shown in Figs. 255 and 256.

This balance was designed by Bairstow and the staff of the National Physical Laboratory for the experimental investigation of the stability of aeroplanes. The main part of the balance consists of two arms at right angles, each arm being counter-balanced. The central lines of these arms meet in a point at which a steel centre is fixed. The weight of the balance is taken on this point, which rests in a hollow cone in a column from the floor. The vertical arm of the balance passes through the under-

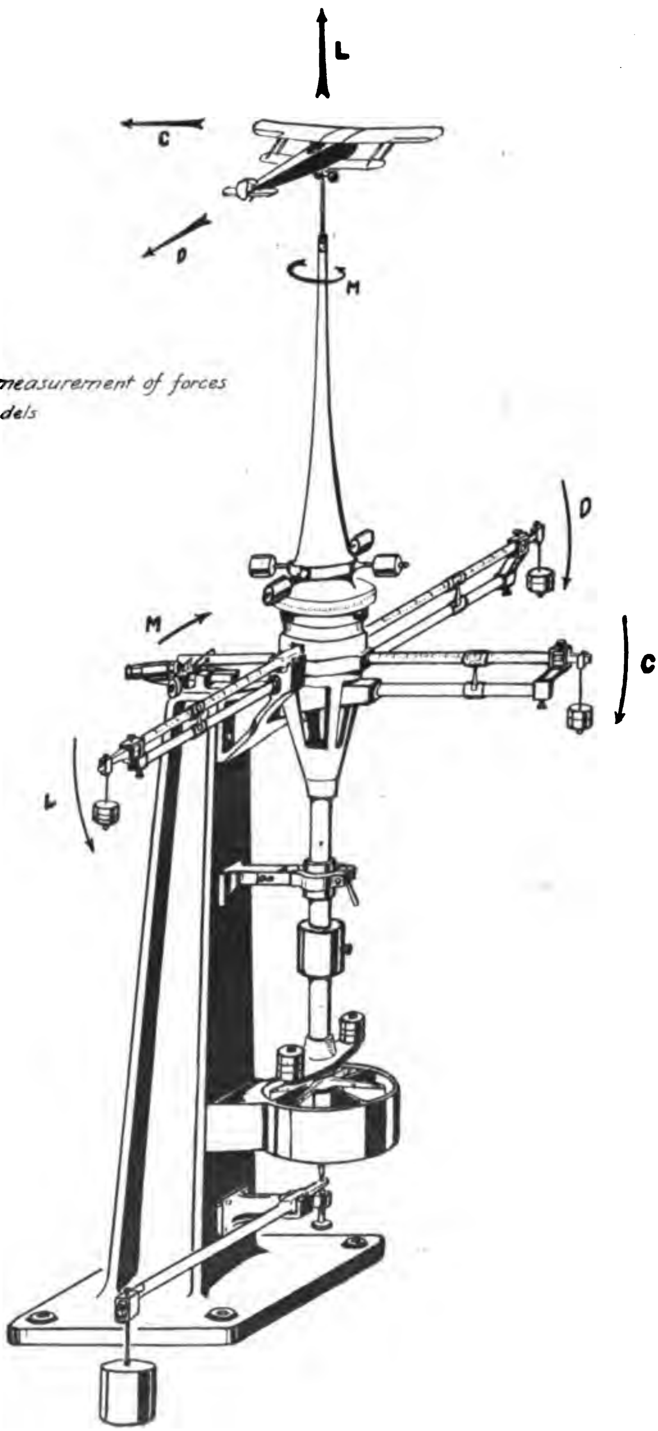



*Fig. 255*
*Balance for measurement of forces on aircraft models*

side of the channel and supports the model under test. The horizontal arms are very carefully set parallel and at right angles to the wind direction. This first arrangement of the balance allows of the measurement


of the forces on the model along two fixed rectangular axes, the cross wind, $C$, and down wind, $D$, the balance being prevented from rotating by the use of a spring clip and strut, on one arm. The model may be set relative to these axes by means of a graduated circle on the upper part of the balance.

The forces on the model due to the wind are measured by weights hung on the ends of the arms and a sliding jockey, oscillations being damped out by an oil dash-pot at the lower end. This dash-pot is divided into four compartments to admit of greater or lesser damping independently on either axis. In the estimation of the moments $M$, about the vertical axis, a cup is brought up into contact with the lower end of the balance, and the balance released to turn about the vertical axis. The moment is measured by means of a cantilever spring displaced by micrometer, a microscope and cross-wire being used to adjust the balance to its zero position.

Still another arrangement is employed to measure the vertical lift $L$. This is effected by lifting the entire balance parallel to itself by means of two levers, a heavy counterpoise being used on one lever while the other is utilised for measurement of the variation in the force due to the wind. This measurement involves a troublesome correction due to decreased pressure in the channel tending to lift the oil seal at the point where the vertical arm of the balance enters the channel. Enclosing the entire balance and observer in a chamber in pressure equilibrium with the channel would probably eliminate this and other practical difficulties. In measuring the forces on wing sections and certain other stream line components, it is possible to have a ratio as high as 18 to 1 between the forces on two arms, and it is therefore extremely important that the axis of one arm should be along the wind in order to avoid a component of this force coming into the measurement of the other. Great care is therefore necessary in setting up the balance to verify by actual experiment that this adjustment is correct.

Four balance weights are provided at the base of the vertical arm of the balance, by means of which the centre of gravity of the rotating part of the vertical arm and the model attached to it can be arranged to lie in the axis of rotation when the angle setting of the model is varied. On the lower part of the balance, weights can be placed which permit changes to be quickly made in the sensitivity. The normal sensitivity of the balance is about one-thousandth of a pound, and a single steel point has been found capable of carrying a load over 120 lb. dead weight.

*Extrapolation of Data for Models to Full Scale.*—The conversion of scale model results to data for the full-sized machine is based on the Principle of Dynamical Similarity already referred to in connexion with the flow of fluids in pipes. As we are considering bodies of identical shapes, but different in size, the length $l$ of one part will determine the size of the body.

On consideration it will be seen that the forces acting on a body placed in a wind-stream can only depend on the size of the body, its shape, the density and viscosity of the air. Hence the expression for the resistance of the body must contain these quantities and these quantities only, and, further, it must be of the dimensions of a force, i.e. $\frac{[M]\,[L]}{[T]^2}$

$M$ denoting mass.
$L$ ,, length.
$T$ ,, time.

So if the quantities $l$ the length ; $\rho$ the density ; $\eta$ the kinematical viscosity, and $V$ the velocity are grouped together in an expression which has the dimensions of a force, this will be the function for the resistance of the body. Now the dimensions of these quantities in terms of length, mass and time are :—

$$\text{Density } \frac{M}{L^3}$$

$$\text{Velocity } \frac{L}{T^2}$$

$$\text{Kinematical viscosity* } \frac{L^2}{T}$$

Since these quantities alone enter into the expression for the resistance of the body it follows that the general form $\rho^x V^y l^z \eta^w$, or a series of such terms, must be capable of expressing the resistance provided that the values of the indices $x$, $y$, $z$ and $w$, are chosen to give it the dimensions of a force to the expression. By substituting the dimensions of $\rho$, $V$, etc., it can be shown that expression reduces to

$$\rho V^2 l^2 \left(\frac{Vl}{\eta}\right)^w$$

In which $w$ cannot be determined, since the quantity $\frac{Vl}{\eta}$ has no dimensions. Hence the law of resistance must take the form

$$R = \rho V^2 l^2 f\left(\frac{Vl}{\eta}\right)$$

the exact form of the function $f\left(\frac{Vl}{\eta}\right)$ being mathematically indeterminate and can only be found by experiment.

* As previously explained, the kinematical viscosity is the (viscosity/density) and since the coefficient of viscosity of any fluid is defined as the tangential force on unit area over one face of a plate of a fluid which is required to keep up unit distortion between the faces, it follows that it has the dimensions $\frac{M}{TL}$ so that the kinematical viscosity will be of the dimensions $\frac{L^2}{T}$.

So that two geometrically similar bodies of two sizes moving at different speeds will have the same form of expression for the function, but the values of $Vl$ will be different in the two cases.

If, however, comparisons are made in one medium, for example, air, $\rho$ and $\eta$ are identical for the two cases, and if the appropriate values of $V$ are chosen so as to make $V_1l_1$ equal to $V_2l_2$ the resistance coefficient will be the same.

The general formula

$$R=\rho V^2l^2f\left(\frac{Vl}{\eta}\right)$$

serves as the basis for correlating experiments with different-sized models and comparisons with full scale, since it is clear that the form of the function $f\left(\frac{Vl}{\eta}\right)$ can be determined if a series of values of the resistance coefficient $\frac{R}{\rho V^2l^2}$ are plotted against the corresponding values of $\frac{Vl}{\eta}$. From such a curve the value of the resistance coefficient can be obtained for any particular values of $Vl$.

It is found by experiment for most stream-line bodies the value of the $f\left(\frac{Vl}{\eta}\right)$ approximates to a constant for high values of $Vl$, and the resistance then varies as $V^2$, as shown by the above formula for $R$. Assuming this constancy in the value of $f\left(\frac{Vl}{\eta}\right)$ to hold up the values met with in full scale machines, it is obviously possible to predict its performance.

Owing to practical difficulties the values of $Vl$ used in model experiments are relatively small compared with those for a full-sized machine, their usual magnitude rarely exceeding one-tenth—also the function varies somewhat rapidly over the experimental range, and in view of the instability of the flow in the vicinity of the model several resistance curves may be obtained for the same body. So it is essential that the correct curve for extrapolation is found by using sufficiently high values of $Vl$.

In predicting the performance of full-scale machine from models it must also be remembered that no account is at present taken of the propeller wash which is an important factor. As an extreme example of this effect it might be mentioned that it is necessary to multiply the values found for the control forces on the tail plane and elevator from model experiments by an empirical factor which is approximately two.

Wind channel experiments are capable of affording useful information

and comparative data as to the design of parts such as wing sections, but an accurate and comprehensive series of experiments on full-scale machines are required to establish definitely the form of the $Vl$ curve at the actual values relating to aircraft. Such experiments can only be carried when accurate instruments become available for the measurement of speed, engine thrust, true horizontal and vertical axes.

*Balance for the Determination of the Specific Gravity of Gases.*—The specific gravity of a sample of gas is a physical constant which is frequently required. The standard method of weighing a container full of gas, then exhausting and weighing again, is a tedious operation, since the weighings must be done with a high degree of accuracy to obtain the small difference due to the weight of the gas.

Another method which has been used successfully by Gray, Aston, Ramsay, Edwards, and Hans Pettersson, is based upon the fact that the buoyancy effect of a gas is directly proportional to its density. Since the density is proportional to the pressure by varying the pressure of the gas it is possible to adjust the buoyancy force upon an object weighed in it within certain limits. Hence the ratio of the densities of two gases may be calculated from the values of the pressures at which they produce the same buoyancy effect under the same conditions. This method was found to be particularly convenient in the determination of the densities of the rare gases owing to the fact that minute quantities of the gases sufficed for the experiment. The essential components of the balance employed will be seen from Fig. 257.

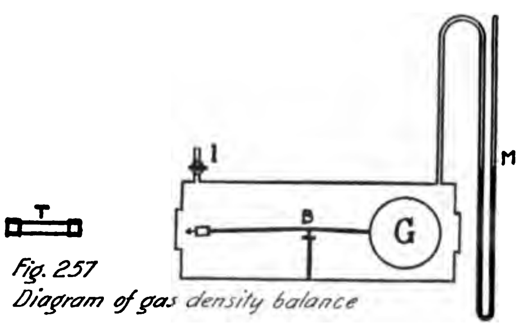


Fig. 257
Diagram of gas density balance

The balance beam $B$ carries at one end a sealed globe $G$ and a counterpoise at the other. In vacuo the moment of the globe about the knife-edge exceeds that of the counterpoise, and equilibrium is obtained by varying the gas pressure in the enclosure until the buoyancy effect on the globe is sufficient to counteract this. Then the value of this pressure is proportional to the specific gravity of the gas.

The most recent type of micro balance is that described by T. S. Taylor in the *Physical Review*, 1917. He found that balances having knife-edge and plane supports did not possess an entirely reliable zero position, and was led to try a quartz fibre instead of the knife-edge support. His method of construction was as follows :—

The balance without its case is shown in Fig. 258. It consists essentially of two parts: a framework of small quartz rods having a bulb and counterpoise, and a large quartz rod bent up in the shape of a flattened U between the legs of which the framework was suspended by quartz fibre. The framework or beam was made of quartz rods about

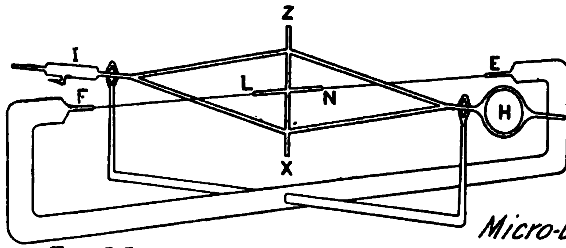



Fig. 258 Micro-balance for density of gases

three-fourths of a millimetre in diameter. A hollow bulb $H$, about one centimetre in diameter, was attached at one end of the longer diagonal of this framework, and a solid mass of quartz $I$ was attached at the opposite end of the same diagonal as a counterpoise. Such a framework is readily made by placing the quartz rods, bulb, and counterpoise in a form of the desired dimensions previously cut in a flat slab of graphite and then fusing the rods together by means of the oxy coal-gas flame. The entire mass of framework, including the bulb and counterpoise, was slightly under one gram. From the ends of the rod $L\ N$, which was perpendicular to the plane of the framework at its mid point, fine quartz fibres were drawn out and, being stretched taut, their ends were fused at $F$ and $E$ to the legs of the flattened U made of a heavy quartz rod. Thus the framework upon which the bulb $H$ and the counterpoise $I$ were attached was supported by the quartz fibres $F\ L$ and $N\ E$ with its plane of figure vertical and at right angles to the line joining $F$ and $E$.

The balance was adjusted so that its centre of gravity was very slightly below the line $L\ N$. This is readily done by adding small quantities of quartz to the ends of the rods $X$, $Z$, or those attached to $I$ and $H$. The final adjustment is obtained by holding the desired end of a rod for a few seconds in the oxy-gas flame, thus volatilising a very small quantity of quartz. Quartz rods were fused at right angles to the mid point of the support rod and to these were attached the forked supports near $I$ and $H$, as shown in Fig. 258. These supports prevented the balance from producing too great a torsion on the supporting fibres when a considerable difference in the buoyancy upon counterpoise and bulb existed, and also permitted the balance to move but slightly from what might be

called the equilibrium position. The equilibrium position is that for which the line drawn through the centre of the bulb $H$ and the counterpoise $I$ is horizontal.

The case in which the balance was placed was a bronze casting having its internal cavity in the form of a cross, the same as that of the balance and of such size as to allow the balance to be slipped readily into it. The case being made in this shape made it possible to use a relatively small volume of gas. It was so constructed that it could be evacuated or withstand considerable internal pressure and remain gas-tight.

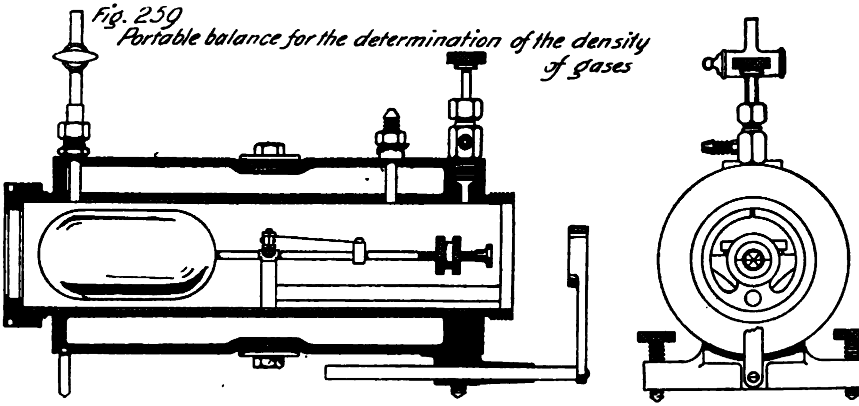
The balance was adjusted in the manner mentioned above, so that when it was placed in air at a pressure of about one-sixth of an atmosphere, it was in equilibrium position. This position could be observed by looking through a window in the case at the small tip of quartz below the counterpoise $I$. This was done by means of a low-power micrometer microscope. The reading of the microscope which corresponded to equilibrium position was 26·00. The balance thus adjusted was cleaned by boiling in nitric acid and washing in distilled water. It was thoroughly dried in an oven and placed in the case. The case was then made tight by waxing and screwing down its cover.

Balances based on the same principle have been long used for the determination of variations in the specific gravity of coal gas, and recently the design has received careful study at the Bureau of Standards by Mr. J. D. Edwards with a view to developing a form suitable for field use in the determination of the density of "natural" gas. Sectional and end views of Edwards' balance are given in Fig. 259, and the following is the method of construction :—

The balance case and its water jacket are made up of brass tubing and cast metal end pieces, or may be cast in one piece, as shown in the figure. Aluminum may be used in the construction in order to make the apparatus as light as possible if this is desired, but a heavier form has the advantage of greater stability. Lining the casting with a thin piece of drawn metal tubing may be necessary in order to eliminate any leakage due to microscopic holes in the case casting. The ends of the gas chamber are closed by brass screw caps which have glass windows fastened in with Khotinsky cement. A small, soft rubber washer set in an annular ring in the cap enables one to screw it on to form a gas-tight joint without the use of tools. The water jacket is filled or drained through the openings in the top or bottom, which are closed by screw plugs. The glass stopcock (shown at the left end of Fig. 259), cemented into a metal union, provides means for introducing gas and air. A small drying tube can be

attached to this by means of a rubber tubing. At the other end of the balance is shown a needle valve which is used for the fine adjustment of pressures. With this needle valve any gas in excess of the required pressure can be let out gradually. This eliminates the use of a bulky and inconvenient levelling bottle. Adjacent to the valve is shown a connecter to which is attached by means of a union a small copper tube leading to the U-gauge. The beam and globe are made entirely of metal in order to give them the strength desirable for field work. The globe,

Fig. 259
Portable balance for the determination of the density of gases



which is made of spun brass, is soldered to a bronze tube, the other end of which is threaded to carry the lock nuts used as counterweights. The cross-arm is carried on a vertical pillar which is rigidly attached to the beam. A pair of lock nuts hold it rigidly to the pillar and permit changing the centre of gravity (and therefore the sensibility) of the beam by raising or lowering the needle points. Any turning of the beam on the pillar is prevented by a strip of metal fastened to both cross-arm and beam, which keeps the needles in a plane at right angles with the axis of the beam.

The needles forming the "knife-edge" of the beam are carried on a small metal cross-arm and rest in a half cylinder of glass which serves as a bearing surface. The use of a small glass hemisphere as the bearing support for one of the needles was not entirely satisfactory in practice. Although it kept the beam centred in the case, there was a tendency for the needle to bear on the side of the hemisphere unless the bearing support was exactly horizontal, and any imperfection in the bearing surface tended to increase in effect since the needles continually bore on the same small area. With the cylindrical bearing on both sides, no difficulty was experienced in keeping the beam centred except where there was excessive vibration from machinery, in which case it might be necessary, for the

sake of expediency, to use the hemispherical bearing. The needles can be removed or their length adjusted by loosening the set screws near the ends of the cross-arm. Any sewing needle with a fine sharp point can be used. Phonograph needles are not satisfactory for this purpose unless they are first sharpened by polishing them in a lathe with an oil stone.

The bearings are cemented into a support, which is held rigidly in place by means of a rod attached to a split ring which fits tightly into the end of the case, as shown on the right. This ring carries at its centre a small glass window across which a line is ruled to serve as a reference line in balancing the beam. A nut on the end of the beam is faced with celluloid and bears a pair of cross-lines. A small magnifying glass is mounted in the vertical arm, shown at the end of the apparatus in the side view, but not shown in the end view. The glass can be focussed on the reference line and the crossed lines on the end of the beam, making their adjustment to coincidence accurate and convenient.

The accessory apparatus required with the balance are a U-tube manometer, barometer, vacuum pump, and means for drying the gases.

*The Arndt Gas Balance.*—An ingenious application of the fact that a

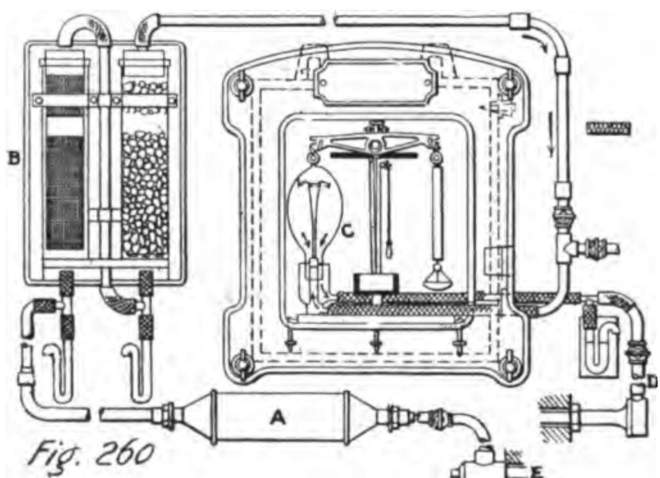



Fig. 260

given volume of carbon dioxide weighs about one and a half times as much as an equal volume of air has been made by Arndt. He has developed a method of estimating carbon dioxide in flue gases by using a balance of the equal arm type (Fig. 260). The method of operation of the instrument is as follows :—

The gases are drawn continuously from the flue at $E$, by means of the steam jet $D$. On their way through the apparatus they pass first through the filter $A$ and drying tubes $B$, and then through the weighing

bulb $C$. The scale of the balance is graduated so that the percentage of $CO_2$ can be read off directly. The balance has to be of a fairly sensitive type, since the weight of a litre of pure $CO_2$ is only 1·97 gms. as compared with 1·29 gms. for an equal volume of air, and for maximum efficiency in the boiler plant the $CO_2$ content in the flue gas must lie between 12 and 14 per cent. So the density effects which have to be measured are relatively small. The instrument is made in a form suitable for erection in the boiler house.

*Recording Densimeter for Liquids.*—A well-known method for determining the density of a liquid is to observe the apparent decrease in

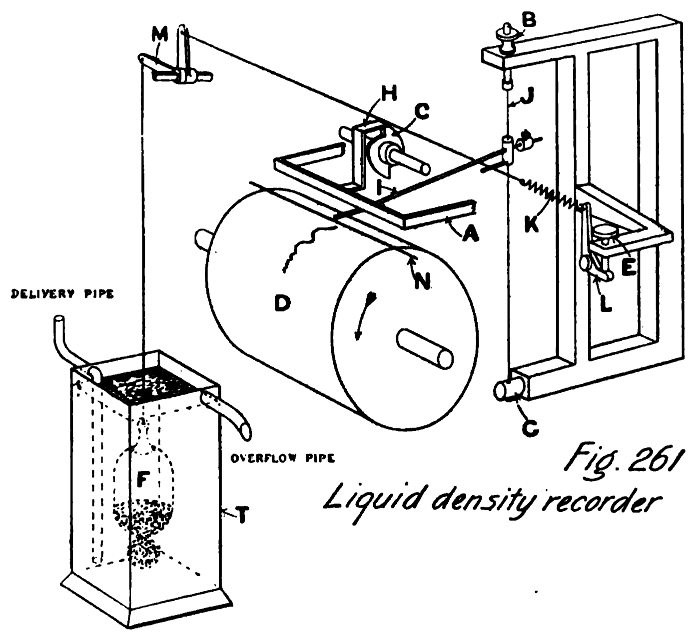



Fig. 261
Liquid density recorder

weight of a solid of known volume when immersed in the liquid. The Cambridge Scientific Instrument Company have devised a simple recording instrument based on this principle, which is shown diagrammatically in Fig. 261.

The float $F$ of quartz is totally immersed in the solution under test, a sample of which is passed through the tank $T$. The float rises or falls with the variations in density of the solution. It is connected by means of a vertical thread or fine wire to the bell-crank lever $M$, which further transmits the movements to the boom $I$. This boom is attached to the vertical steel wire $J$, and counterpoised by means of a weight. The movements of the boom are adjusted by the resistance to torsion of the steel wire, and also by the helical spring K. The boom $I$ swings above

the drum $D$ of the recorder. This drum is rotated by clockwork at a definite speed of one revolution in twenty-five hours, or two hours five minutes, whichever is required. The drum carries the recording paper, and between the pointer and the drum an inked thread is drawn in a direction parallel to the axis of the drum. A clock-driven cam operates the cam wheel $C$, which allows the presser bar $A$ to depress the pointer at half-minute or one-minute intervals, which in its turn depresses the inked thread on the surface of the recording paper. A visible record of the instantaneous positions of the pointer is thus produced as a series of dots which practically form a continuous line. In the intervals between the depression of the bar, the pointer is free to take up another position, and thus errors due to mechanical friction are eliminated. The tank is placed below the recorder, underneath the hole in the bottom of its case. The walls of the tank are of wood, lined with fused lead to permit of its use with acid and alkaline solutions. A full scale deflection of 80 mm. usually corresponds to a 2·5 per cent change in the density of the solution.

*Torsion Balances.*—Balances in which a force is measured by utilising the torsion of a wire have been devised in a variety of forms to meet special requirements. In Fig. 262 is illustrated a surface tension apparatus devised by Dr. du Nouy of the Carrel Mission, and made by the Central Scientific Company. The arm carries a wire ring resting on the surface of the liquid and the force required to pull it away against surface tension is measured by the torsion of the supporting wire. One end of the wire is fixed, while the other is attached to a worm and wheel which can be rotated slowly and the deflection observed by the position of the pointer. Torsion balances have also been devised for weighing. A balance for the weighing of quantities of material from one-thousandth of a milligram to two milligrams is shown in Fig. 263.

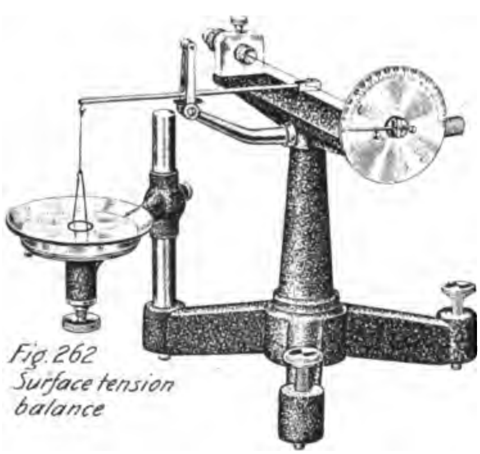


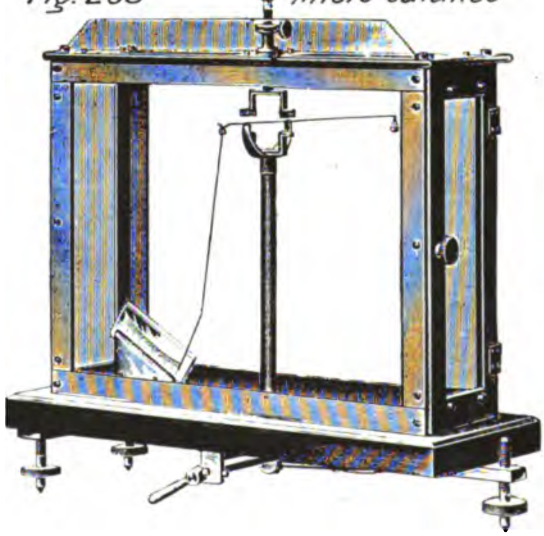
Fig. 262 Surface tension balance

*Micro Balance.*—Hertz, in 1882, suggested a form of balance in which the torsion of a silver wire was utilised, and in the hands of Nernst the torsion balance became an instrument of precision. The chief improvement effected by Nernst was the substitution of a quartz fibre for the

metallic wire. Quartz fibre has the unique property of being practically free from elastic fatigue.

*Nernst's Micro Balance* (Fig. 263).—A very fine quartz thread about 5 centimetres long is placed horizontally between the prongs of a brass fork, supported vertically on a pillar 16 centimetres high. Crosswise on it rests the capillary glass, 30 centimetres long, 0·5 millimetres diameter, which constitutes the balance beam ; this is fixed, by means of sodium silicate, to the quartz thread. On the shorter arm of lever, which is about 9 centimetres long, a platinum hook is fused : on this the pan can be suspended. The long arm of lever is bent downwards at right angles, and tapers into a very fine thread over a graduated glass scale, which is divided into 0·5 millimetres. By observing through a telescope under a good light one-twentieth of each division is discernible. A brass fork is fitted to act as a support. On the left arm of the balance a platinum cursor is attached by means of sodium silicate; this is to counterpoise the scale pan. This form of cursor has been devised to afford the required stability to the balance, without reducing delicacy more than is desirable for the measurement to be effected. The small platinum pan weighs, including the suspension thread, about 20 milligrammes. For weighing small crystals, or for weights, a disc is supplied; this is made of platinum foil 0·8 centimetres diameter by 0·015 millimetres thick ; for decimal weighings, a small capsule is used of the same thickness as the round-plate. The balance is mounted on slate base-plate, fitted with three levelling screws. By turning these one can adjust the balance on the zero point. The balance is designed to weigh up to 2 milligrammes, sensitiveness one-thousandth of a milligramme. The method of suspending the beam by a horizontal fibre has the defect that the stress on the fibre is much greater than the actual weight of the beam.

Fig. 263 Micro-balance



Hans Pettersson has recently described an improved type of micro balance capable of weighing to one-millionth of a milligram. This balance

in general arrangement is similar to that of Gray and Ramsay, but is suspended by two vertical fibres on the same lines as the Kelvin ampère balance. The balance is enclosed in an air-tight case, and changes of weight are balanced by varying the pressure, a quartz counterpoise being suspended from one arm of the beam. An alternate method is to hang a steel needle from the end of the beam and apply an attractive force by means of a solenoid wound around the containing tube. The beam is relieved off its stops by the operation of a magnet outside the case.

*Current Balance.*—Probably the most frequently measured quantity in electrical engineering is that of electric current, since with a constant voltage circuit it gives a direct indication of the power being consumed at any instant. Ordinary ammeters operate on the principle of balancing the force due to the current by the torsion of a spring somewhat similar to the hair-spring of a watch. For absolute measurements and work of the highest precision the permanency of the ordinary type of instrument cannot be relied upon, and recourse is made to the current balance. In this instrument the force exerted between two coils, carrying the current to be measured, is balanced against a known weight, and the magnitude of the current is then calculated from the weight required and previously determined constants of the coils.

In the standard current balance installed at the National Physical Laboratory, which is illustrated in Fig. 264, there are two moving coils and four fixed coils, the latter being wound in pairs on two marble cylinders. The scale-pans of an ordinary type precision balance are replaced by two circular coils of wire wound on marble cylinders whose axes are vertical. Considering one side of the balance only, the movable coil is adjusted to hang freely within the large marble cylinder upon which the two fixed coils are wound and with its plane midway between the two and coaxial. The three coils are so connected that an electrical current may be passed through them in series—through the movable and the lower fixed coil in one direction, and through the upper fixed coil in the opposite direction. Thus when the electrical current is flowing through the coils, the movable one is attracted towards the lower, and repulsed by the upper fixed coil. The current circulates in the opposite sense in the set of coils on the other side of the balance with the result that there is a resultant downward force. This force is balanced by the addition of appropriate weights to the pans. The constant of the balance is obtained from direct measurement of the linear dimensions of the coils. The four coils are wound with a single layer on marble forms to facilitate measurement.

In Fig. 264 the fixed coils are lowered so as to expose the smaller moving coils suspended from the balance arms. The current is led to and from the moving coils by festoons of very fine wire to reduce to a minimum any constraint on the motion of the beam. The balance beam and subsidiary parts are identical in construction with those met with in the usual type of precision balance. The pans are replaced by the moving coils and suspensions, while provision is made for the addition or removal of a weight from either side. In practice the procedure is to adjust the current so that on reversal of the current the transfer of a

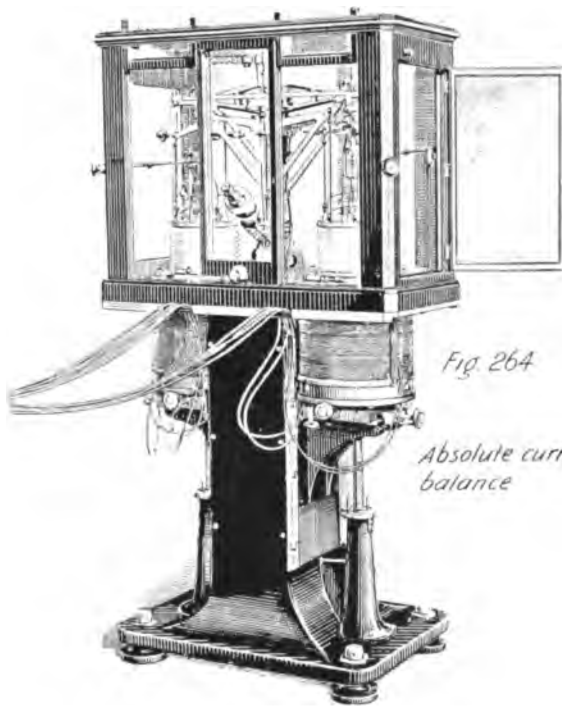


Fig. 264

Absolute current balance

certain weight from one pan to the other will restore equilibrium. A current of one ampère is balanced by a mass of about eight grams. The entire instrument is carried on a massive phosphor bronze stand tested for magnetic impurities. When in adjustment, each moving coil is situated so that its end planes coincide with the mean planes of two fixed coils of the same length, wound upon opposite ends of the same hollow marble cylinder. The axes of the moving coils are vertical and coincide with the axes of the fixed coils.

It should be noted that the above balance is really a double instrument, symmetrical with reference to the plane through the central knife-edge and normal to the beam. Each pair of coils would function as a

current balance and, as a matter of fact, the Board of Trade balance is equipped with one such set of coils only. The symmetrical arrangement has advantages when the highest degree of accuracy is desired, since the influence of the earth's magnetic field is eliminated as well as any effect due to inequality in the arms. Instruments on the same principle, but differing radically in detail of construction, have been largely used for current measurement in technical practice and are known as Kelvin's ampère balances. A small balance of the same type as the standard current balance was used by Anderson in an investigation in which it was necessary to observe the change of a material in vacuo. Here the weight of the material was deduced from the value of the current required to produce equilibrium, and two pairs of solenoids were arranged so as to release and arrest the beam. A vacuum micro balance, depending on the same principle, but of quite a different design, has been described by Urbain.

*Determination of the Earth's Mean Density.*—Probably the most difficult weighing operation ever performed with the equal-arm type balance was the determination of the gravitational constant, or as it is sometimes referred to in the popular press "weighing the earth." As is well known, the weight of a body is the force with which it is attracted to the earth. Newton first enunciated the law of gravitation, and indicated its universal application. Expressed mathematically the law states that the mutual attraction between two particles $M_1 M_2$ at a distance $d$ apart is proportional to $\frac{M_1 M_2}{d^2}$.

Hence, if the force of attraction between two known masses can be measured it is possible to calculate the mass of the earth from a knowledge of the weight of one of the masses, and assuming the value of the earth's radius from survey and astronomical observations. In an experiment by Poynting a spherical mass of 20 kilograms was suspended from the arm of a large balance. When another mass of 150 kilograms was brought near (the distance between centres of two masses was 30 cms.) an attraction equivalent to a weight of $\frac{1}{4}$ milligram was observed. It can be proved theoretically that the force between two spheres of finite radius is exactly the same as if their masses were concentrated at their centres. Now the earth's pull on the 20 kilograms is 20,000 g. dynes, while the pull due to 150 kilograms is 0·00025 g.

Hence the ratio of the two forces is eighty million to one. Now the force varies inversely as the square of the distance. Hence, neglecting the

distance of the mass of 20 kilos above the earth's mean surface and taking the value of $6 \times 10^8$ cms. for the earth's radius, we have :

$$\frac{\text{Mass of Earth}}{(\text{Radius})^2} : \frac{150{,}000}{30^2} = 1 : \frac{1}{80{,}000{,}000}$$

So that the mass of the earth is approximately $5 \times 10^{27}$ grams.

V. Jolly, in 1878, first used the common balance for this experiment, and the method was considerably improved in detail by Poynting in 1899. The balance he employed is identical with the ordinary precision balance in detail but on a much larger scale, the beam being 4 ft. in length. A diagrammatic view of the arrangement of the apparatus is given in Fig. 265. The balance was contained in a closed room on very firm foundations. From the arms of the balance two lead spheres, each of 20 kilograms, were suspended, while the attracting mass $M$ of 150 kilograms was fixed on a turn-table capable of being brought under each suspended mass in succession. The effect on the balance was thus doubled. The small mass $m$ was half that of the big mass $M$ and was placed at twice the distance from the centre of turn-table to counter-balance the weight, otherwise a tilt of the floor was produced by the transfer of the 150 kilos from one side to the other. To eliminate the effect due to the attraction of the big mass on the balance beam and suspensions the experiment was repeated with the 20 kilograms masses in the position $A^1$ and $B^1$. In both experiments the attraction on the beam would be the same, so the difference observed would be solely due to difference in the distance between the attracting masses. The motion of the beam was observed with a telescope and mirror. This mirror was suspended from two parallel fibres, one of which was attached to a fixed support, while the other was fastened to the pointer of the balance. Thus any movement of the pointer

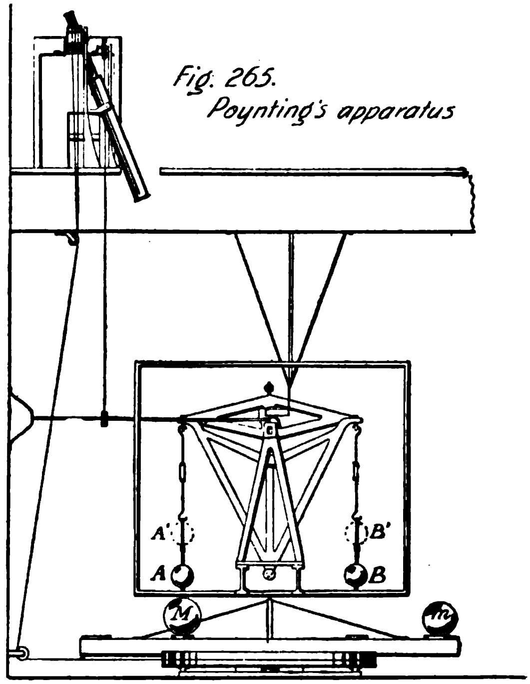



Fig. 265.
Poynting's apparatus

caused the mirror to twist about an axis midway between the two suspensions. By this means the motion of the beam was magnified one hundred and fifty times.

From the observed motion of the spot it was calculated that the attracted weight moved through a distance of about one eight-thousandth of an inch when the large mass was brought beneath. The magnitude of the pull was determined by calibrating with a rider moved along the beam. The experiment demonstrates the extraordinary sensitivity of the common balance when used under ideal conditions.

### Weigh-bridges

The suspended pan type of balance is not convenient for weighing heavy objects with reasonable facility and accuracy, since the chains or rods which carry the platform from the beam interfere with the handling

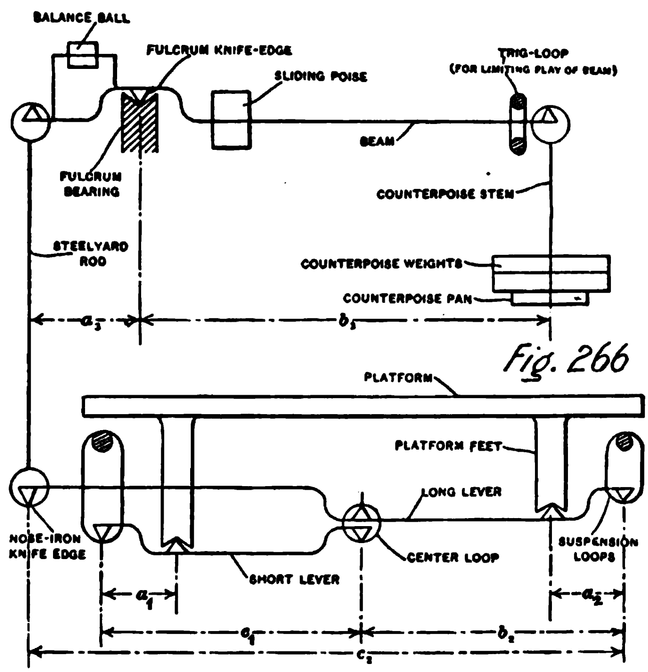



Fig. 266

of the load. Further, the oscillation of the loaded platform about its point of suspension from the beam renders an estimation of the rest-point of the pointer a matter of uncertainty. Consequently in industrial work a type of balance technically known as the stabilised platform scale is generally adopted. Weigh-bridges of this class have a four-point support for the platform, which is constrained to move parallel to itself when the load is applied.

Fig. 266, due to Schlink, of the Bureau of Standards, shows in diagrammatic form the lever system of a common type of platform scale. The small triangles are the knife-edges, and the cross-hatched parts indicate members which are affixed immovably to the frame of the scale. In order that the weight indication may be independent of the position of the load on the platform the following relation must apply :—

$$\frac{a_1}{c_1}=\frac{a_2}{b_2}$$

The leverage ratio $R$, or multiplication of the scale, is defined by the equation :

$$R=\frac{b_3}{a_3}\times\frac{c_2}{a_2}$$

The amount of weight required on the counterpoise pan to balance a given load on the platform is found by dividing the platform load by this ratio $R$. In order that this multiplication may be a definite and unchanging quantity the knife-edges must be affixed to the lever, and not to the connecting element ; they must be sharp and hard enough so as not to flatten appreciably under the loads which they are to carry ; and the knife-edges in any lever must be parallel to each other. The knife-edges in any lever should lie approximately in a single plane, for reasons which will appear later. The planes through the bearing lines of the knife-edges belonging to the several levers must be parallel to one another, and the same is to be said of the loops and rods which connect the levers to each other. In practice, the levers are usually arranged so as to lie with the plane of the knife-edges horizontal and the lines of the connections vertical. These are points which are frequently overlooked by users of this type of scale.

In adjusting the distance between the knife-edges the manufacturer uses standard weights which are hung from the knife-edges, the lever and the attached weights being mounted so as to swing freely as a simple balance. The forces acting on these knife-edges, then, are in the direction of gravity, that is, vertical ; and the parts of the scale when installed must be so placed that the same direction of the forces will obtain. If this is not the case the lever arms of these forces will not be the same as they were at the time the adjustment was made, and the scale will be incorrect.

In these scales the knife-edges are usually made of mild steel, case-hardened, and in the course of time they become rounded and the sensitivity falls off considerably. When this occurs the knife-edges are taken

out and reset by forging and case-hardened afresh. It is obviously very important in these resettings to ensure that the multiplication of the lever system is not altered unwittingly. Hence careful recalibration by the use of standard weights is necessary, and in addition it is desirable to compare the readings for a definite load at various positions on the platform to track variations, if any, in the various levers. Scales of this type range from 1 cwt. to 100 tons maximum capacity. Fig. 267 is a sketch of the arrangement of the levers in a

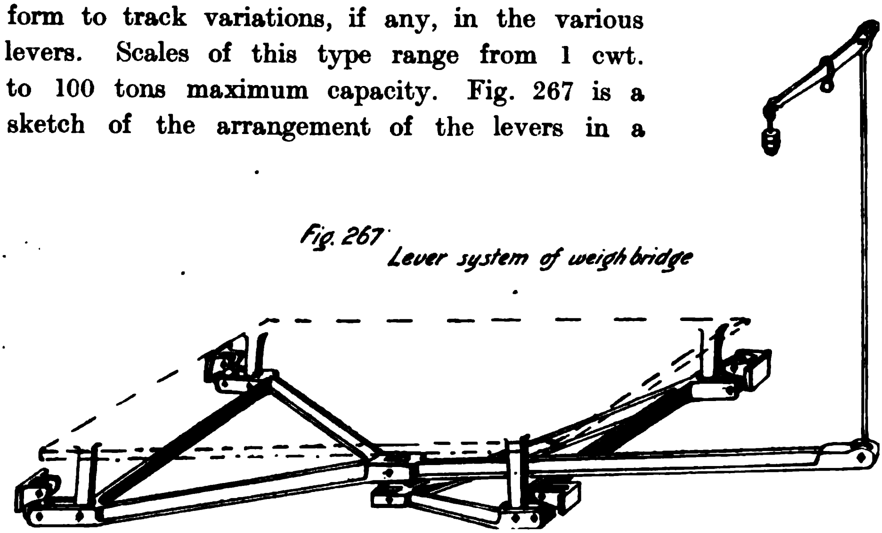


Fig. 267 Lever system of weigh bridge

typical balance in which the platform is shown dotted. A well-made balance of this type is an excellent weighing machine, but unfortunately the cost of the construction is too high to permit of its general adoption for small capacities, such as is required in retail trade. In such cases a link work is provided for obtaining the parallel motion, as shown in the diagram (Fig. 268). It will be observed that here the stabilising link is a simple flat bar provided at each end with holes through which pass pins connecting the bar at its centre to a fixed part of the scale, and at the other ends to the vertical stems supporting the pans. The length of this link between centres of pin-holes, in order that the weight indicated shall be independent of the position of the load on the platform, is required to be equal to the distance between the load and the fulcrum knife-edges of the beam. The pins at either end of the link form pivots. When the load on the platform is displaced from the centre of the platform in the direction of the longitudinal axis of the beam, a stress is set up in the stabilising link,

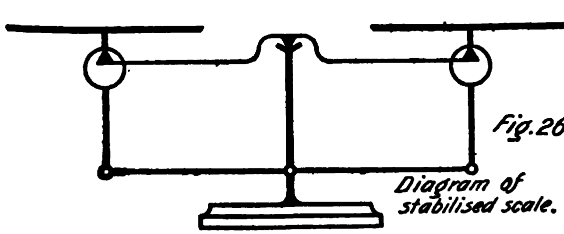
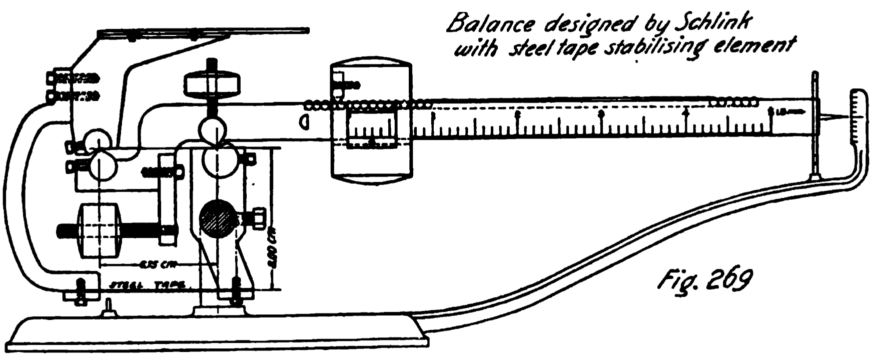


Fig. 268 Diagram of stabilised scale.

accompanied by reactions at each of the pivots above mentioned, and for all such non-central placement of the load a considerable and variable friction will be introduced at these connections, this friction being much greater in amount than that existing between the usual knife-edge and bearing, thus acting to reduce the accuracy of the scale, and to limit the sensitiveness which is attainable under the given construction.

Schlink has devised a balance in which the journal friction is eliminated by replacing the link-work by a flexible steel tape under tension; whilst leaving the scale unaffected as to accuracy and sensitiveness caused by variation in the position of the load upon the platform. An experimental balance with unequal arms embodying the steel tape stabilising element is shown in Fig. 269.

In this scale the knife-edges and bearings were made adjustable to




various inclinations, so as to permit of studying the slipping of knife-edges in their bearings in a direction transverse to the knife-edge axes. The beam of the scale comprises a novel form of notch provision to establish with exactitude the increments of motion of the sliding poise, the notches being constituted by the contiguous surfaces of the upper hemispheres of a row of steel balls set in a straight line and making contact with each other along that line. The extremely high accuracy of commercial bearing balls to equality of diameter and sphericity affords an ideally accurate notching, which will not require the tedious point-by-point adjustment by hand which has formerly been requisite in the case of accurate weighing scales having notched beams. It has been impossible in the case of track scales, for example, to machine the usual triangular notches accurately enough to eliminate the necessity of subsequent hand adjustment. The superiority of this method of construction is clearly shown by the two curves below (Figs. 270 and 271) obtained by Schlink. They represent the damped oscillations of the scale beams

of two balances, one fitted with a steel tape stabilising element and the other with a pin and link check rod. The curves are reproduced from

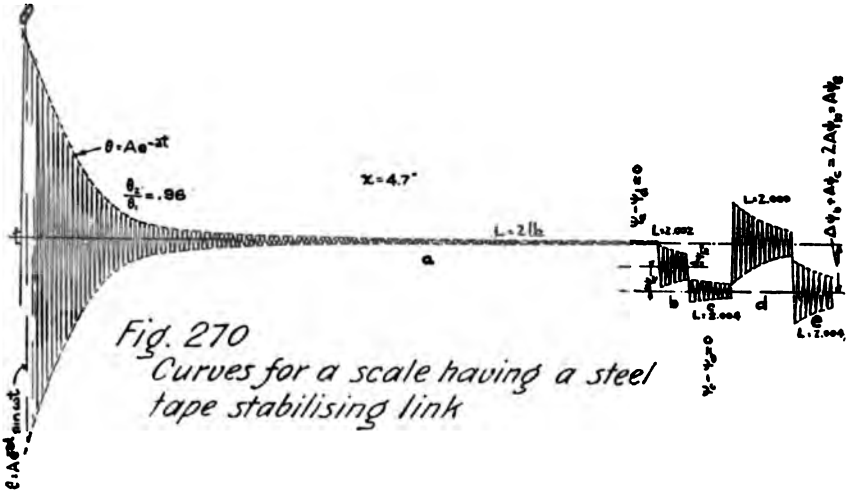



Fig. 270
Curves for a scale having a steel tape stabilising link

photographically recorded oscillograms. They indicate a vibration of the form

$$\theta = A_e^{-at} \sin wt.$$

The horizontal axis is that of time, while the vertical axis is that of angular displacements from the initial plane of balance. The value $\frac{\theta_1}{\theta_2}$ gives a measure of the amount of the damping. The values of the load corresponding to each oscillogram are recorded in each case. For example, in the curves of Fig. 270, $a$ is the oscillation for the scale with a load of 2·000 lb., the distance $x$ from the vertical plane through the load knife-edge being 4·7 ins. In $b$, an increment of 0·112 lb. has been added, and in $c$ an additional 0·002 lb. At $d$, both increments have been removed together, and at $e$, both have been re-added together. Note the accuracy with which the axes of $a$ and $d$, and $c$ and $e$, are collinear respectively. Curves $a$ and $b$ (Fig. 271) are for identical conditions, the scale simply being allowed to come to rest at the end of $a$ and restarted

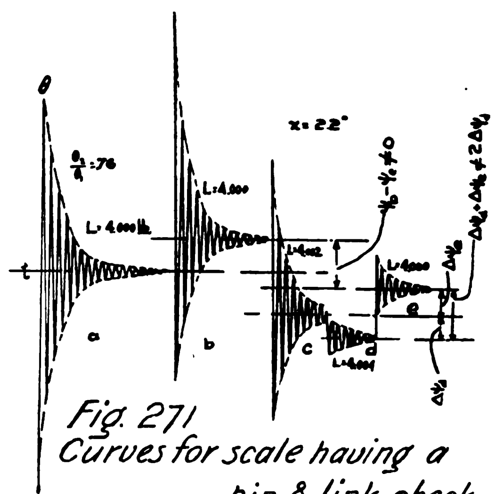



Fig. 271
Curves for scale having a pin & link check rod

for $b$. Note the variability of rest-point here exhibited, and expressed analytically in the equations accompanying the figures.

*Direct Reading Weigh-bridge.*—The adjustment of the counterpoise on the scale arm of weigh-bridge is a tedious operation when a number of weighings have to be performed in succession, as in the case of weighing

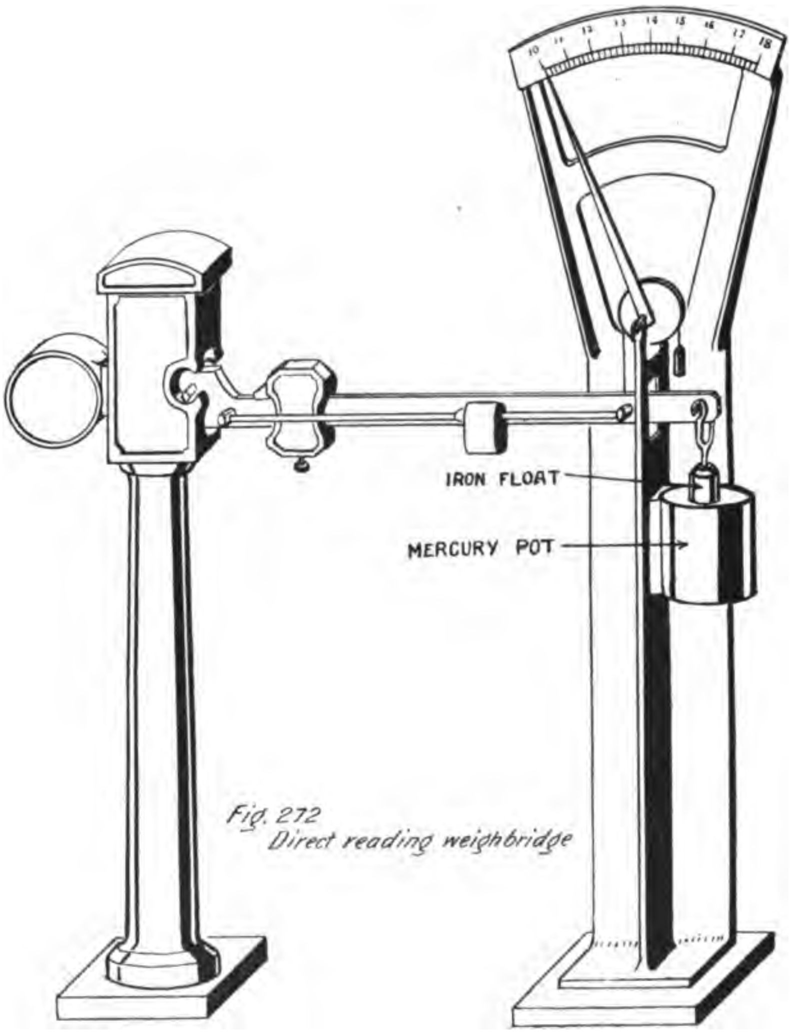



Fig. 272
Direct reading weighbridge

railway trucks or coal "trams" in collieries. Consequently the modern types of weigh-bridges are so arranged as to be direct reading. This is effected by making the counterpoise in the form of an iron block partially submerged in a pot of mercury. Deflection of the lever causes a greater or lesser immersion of the float in the mercury and a proportional variation in the restoring force. A steel band connected to the arm and

wound round a pulley on the pointer magnifies the motion and gives a direct scale reading. Fig. 272 shows the general arrangement of the scale arm and the indicator of this form of weigh-bridge.

### AUTOMATIC BALANCES AND WEIGHING MACHINES.

When it is necessary to weigh a large number of similar objects, for example, coins, or obtain a record of the total weight of a consignment of material transported in bulk, such as grain, it becomes highly desirable to have completely automatic arrangements for effecting the weighing. The earliest machines of this class to be devised were automatic coin-sorting machines, not so much because the work of weighing by hand

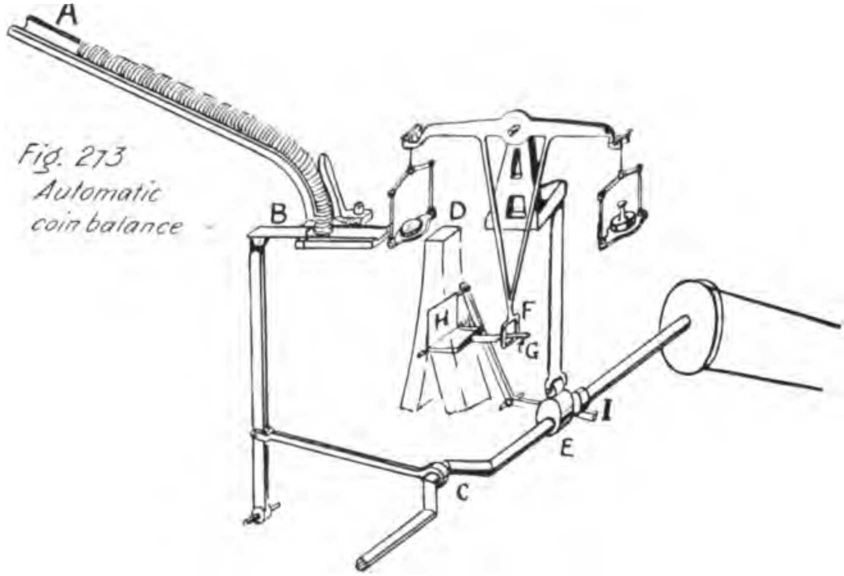



Fig. 273
Automatic coin balance

labour was expensive, but on account of the fatigue created in the operators by the endless repetitions which made their power of observation unreliable.

Coin-sorting machines which gauge the coins according to their weight are now very generally employed by mints and banks. The machines adopted in mints divide the coins, or rather the blanks used for stamping coins, into three groups—" heavy," " medium," i.e. within the tolerance, and " light." The machines used in banks merely separate the coins into two groups, " heavy " and " light " ; the " heavy " being equivalent to the " medium " in a triple machine.

*Automatic Coin-weighing Machine.*—A machine designed and constructed by Oertling is shown diagrammatically in Fig. 273. For simplicity of description a two-group machine is described. The coins are

placed edgewise in the shoot $A$ at the left and slide down so that the pile is vertical on the table of the machine. A reciprocating tongue $B$ operated by a crank $C$ on the driving shaft, passes one coin at a time through a slot on to the pan of an equal-armed balance, displacing the previous coin off the pan into a cavity in the balance table $D$. After a coin is placed in position the rotation of the cam $E$ on the driving shaft lifts the knife-edges and the beam to the weighing position; the weight of the coin is thus compared with a standard placed in the other pan. If the coin is light the beam remains on the right-hand stop, and if heavy on the left-hand stop—the beam does not oscillate. This bias or tilt of the beam actuates the automatic sorting device as follows: the beam carries in lieu of a pointer a small stirrup $F$ which engages with a stepped lever $G$ during the upward movement of balance beam when it is being brought to the weighing position. If the beam is tilted, say, for a light coin, the stirrup catches the shallow notch and carries the lever upward, this movement trips over a deflector in coin passage $H$, and the next coin falling passes out through the right-hand side. If, on the other hand, the coin had been heavy, the stirrup would have been deflected to the right, and allowed the lever to remain horizontal. The next coin would then have passed down the left-hand passage. The deflector is reset after each weighing by a cam $I$, ready for the next cycle of operations.

The triple machine is a slight elaboration of the above, and the lever has three notches instead of two. The coins are allowed to be a definite tolerance below the standard weight, about 0·1 or 0·2 of a grain for gold, and this tolerance weight is placed on the pan hanger of the coin side of the balance. The balances are usually built in duplicate on the same base, and a complete machine is shown in Fig. 274. Such a machine will deal with forty to sixty coins per minute.

*Automatic Grain-weighing Machines.*—Automatic grain-weighers are in extensive use on account of their convenience in dealing with large cargoes of grain and pulverised material generally, such as coal. No external power is necessary for their operation, since the potential energy of the material liberated in its descent from a higher to a lower level is used for driving the mechanism. Essentially the machine consists of a beam balance with the auxiliary gear necessary for operating the balance, and this gear is generally somewhat complicated. The general mode of operation may be described as follows:—

From the arms of the beam is suspended at one end a counterpoise, and at the other the container for the grain. Initially the beam rests tilted over to the side of the counterpoise weight, but when the weight of

the grain is sufficient to counterbalance the beam is raised from its support and sets in operation the automatic motion which performs in succession (*a*) the cutting off of the flow of the grain, (*b*) the emptying of the vessel, (*c*) the closing of the vessel and its replacement in the position for filling, (*d*) the opening of the valve for the flow of grain and recording on a counter one unit for the cycle of operations.

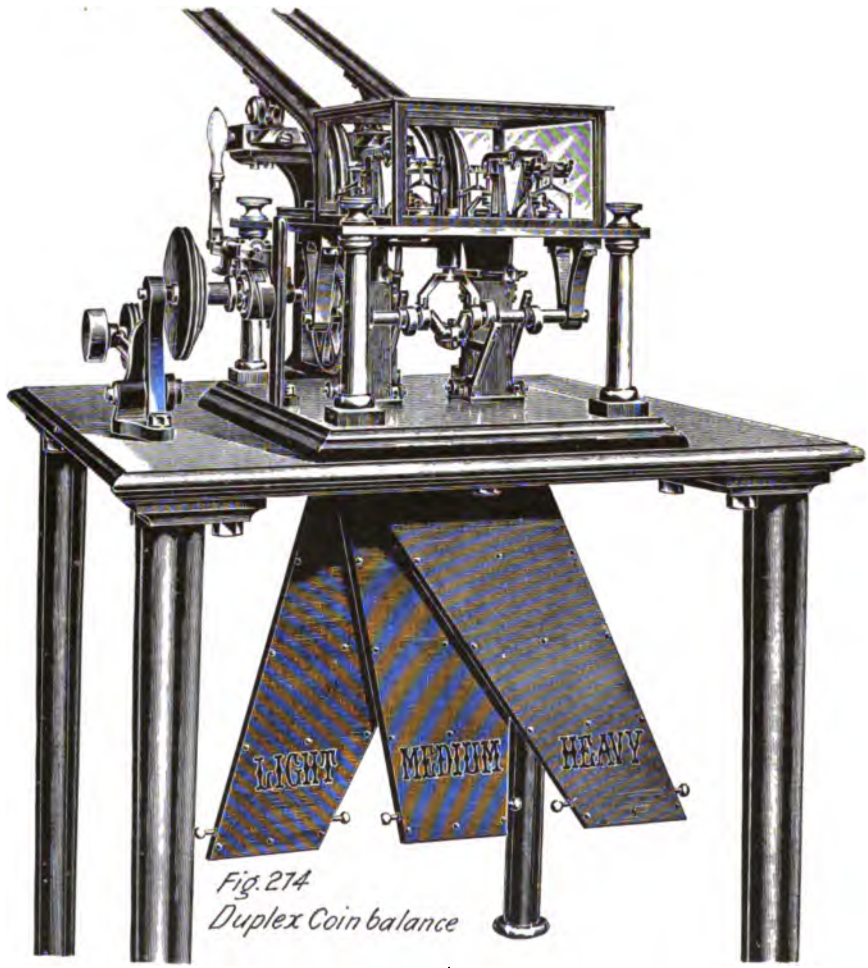


Fig. 274
Duplex Coin balance

The particular difficulty in the design of such balances is to arrange that the supply of grain is cut off at the exact moment at which the weight of grain equal to that of the counterpoise has been obtained and to prevent unweighed grain entering the vessel. It is difficult to solve this problem completely, but the error can be made extremely small by cutting down the filling operation when the vessel has nearly the desired

quantity. Another difficulty is the necessity for interfering with the free motion of the beam to operate the automatic mechanism, and in the design especial care has to be taken to reduce friction on this account to the absolute minimum.

A typical example of an automatic grain-weigher is shown diagrammatically in Figs. 275 and 276, which illustrate the principle of the "Avery" machine. The two side frames, $A_1$ and $A_2$, carry the bearings of the knife-edges of the beam $B$. At one end of the beam is suspended the iron box $D$, and at the other end the receptacle $C$ in which the material is weighed and so arranged that the box $D$ exactly balances the hopper $C$. The former is constructed to hold the required quantity of dead weights, and is made with a sloping top, so that dust does not lodge thereon. The weigh hopper $C$ has a door $C_7$ at the bottom, which is automatically opened and closed when required. The supply of material is regulated from the shoot $F$ by a weighted valve $G$ hinged at $G_1$. A pin, $G_2$, attached to the valve $G$ works in the slot of the lever $H_2$, so that when the locking levers $H_1$ and $H_2$ are down (as shown on diagram, Fig. 276) the valve $G$ is prevented from opening. These locking levers $H_1$ and $H_2$ are connected with the lever $L$ by a weighty rod $K$ fitted with steel roller $K_1$, which, when the rod is raised, rests on the knife-edge fastened to the trigger $M$, the latter being so pivoted as to swing underneath by its own weight. The door $C_7$ at the bottom of the weigh hopper $C$ is kept shut during the weighing operation by the bar $C_3$ attached to the toggle $C_6$; this toggle is pivoted to the hopper, and fitted with a striking bolt $C_8$, which, when the scale is required to weigh automatically, is drawn out until it overhangs the lever $L$. The door is so arranged that when open the weight $C_5$ exerts only a slight tendency to close it, thus a little of the material at the tip will keep it open, and automatically stop the machine from working until the weigh hopper $C$ is empty.

The action of the scale is as follows: On weights to the required quantity being placed in the box $D$, that end of the beam is depressed until the projections on the box $D$ rest on the side frames $A_1$ and $A_2$; the other end rises and by means of the projection $C_{12}$ catching under the pendant $P$ attempts to lift the valve $G$, but being prevented by the locking levers $H_1$ and $H_2$, it only compresses the pendant spring $B_2$. (This also causes the box $D$ and weights to descend gently without any jar to the machine.)

FIRST STAGE.—*The Automatic Weigher receiving the full flow of material at the commencement of the weighing* (Fig. 275).

Then on the free end of the lever $L$ being depressed the other end

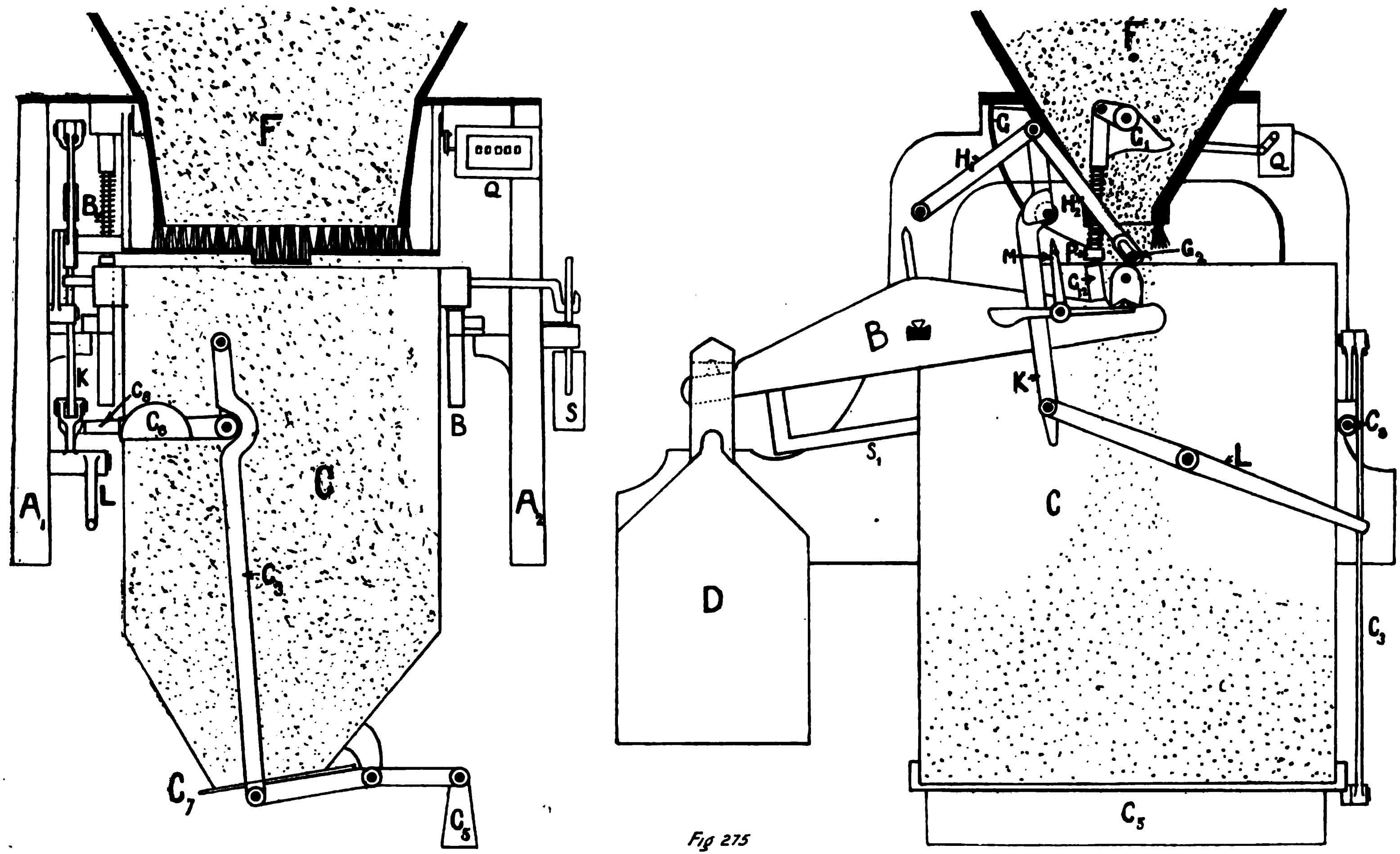



Fig 275

raises the rod $K$ and breaks the locking joint formed by the levers $H_1$ and $H_2$, this frees the valve $G$, which owing to the pressure of the spring $B_2$ flies wide open, lifting the levers $H_1$ and $H_2$ with it, and admits a copious stream of material from the shoot $F$, as shown.

SECOND STAGE.—*The Automatic Weigher receives the diminished flow or dribble of material.*

This stream of material continues until its weight in the hopper $C$, assisted by the weight of the valve $G$, depresses the beam $B$ until it no longer supports the valve, which swings forward as far as the pin $G_2$ in the slot of the lever $H_2$ will allow it. The only material now coming into the weigh hopper is that flowing through the small aperture in the valve $G$, and this amount can be adjusted by means of the screw regulating the length of the slot $H_3$. The levers $H_1$ and $H_2$ are supported by the rod $K$ resting by means of the roller $K_1$ on the knife-edge of the trigger $M$.

THIRD STAGE.—*The supply of material cut off and the mechanism in the act of falling to lock the valve G and to discharge the weigh hopper*

This dribble of material, as just described, continues until the weight of material in the weigh hopper $C$ is equal to the dead weights in the weight box $D$. When the beam descends to the horizontal and by means of the projection $C_{10}$ draws away the trigger $M$ from beneath the rod $K$, which falls and brings the levers $H_1$ and $H_2$ with it, these together with the pin $G_2$ completely shut the valve $G$ and lock it as before.

FOURTH STAGE.—*Shows the Automatic Weigher discharging* (Fig. 276.)

The falling of the rod also raises the free end of the lever $L$, which, by catching the striking bolt $C_8$, opens the door $C_7$. This remains open until all the material has been discharged, when the door swings to again, the striking bolt $C_8$ depresses the lever $L$ which automatically starts the whole operation again.

*Note.*—It will be noticed that when the weight of the material in the hopper $C$ exactly balances the weights in the box $D$, the valve $G$ immediately shuts, but the material in suspension at the time falls into the hopper and would be overweight were it not compensated for by an adjustable weight $S$ on the bar $S_1$ which rests on the beam. $Q$ is an ordinary register or counting apparatus worked by levers from the valve $G$. This counting arrangement keeps an exact record of the number of times the machine operates.

*Crane Balances.*—It is, of course, a very great convenience in heavy goods transport to be able to weigh the goods during the time of loading, and consequently the development of weigh-bridges suitable for insertion in the chain carrying the load have received careful consideration. In

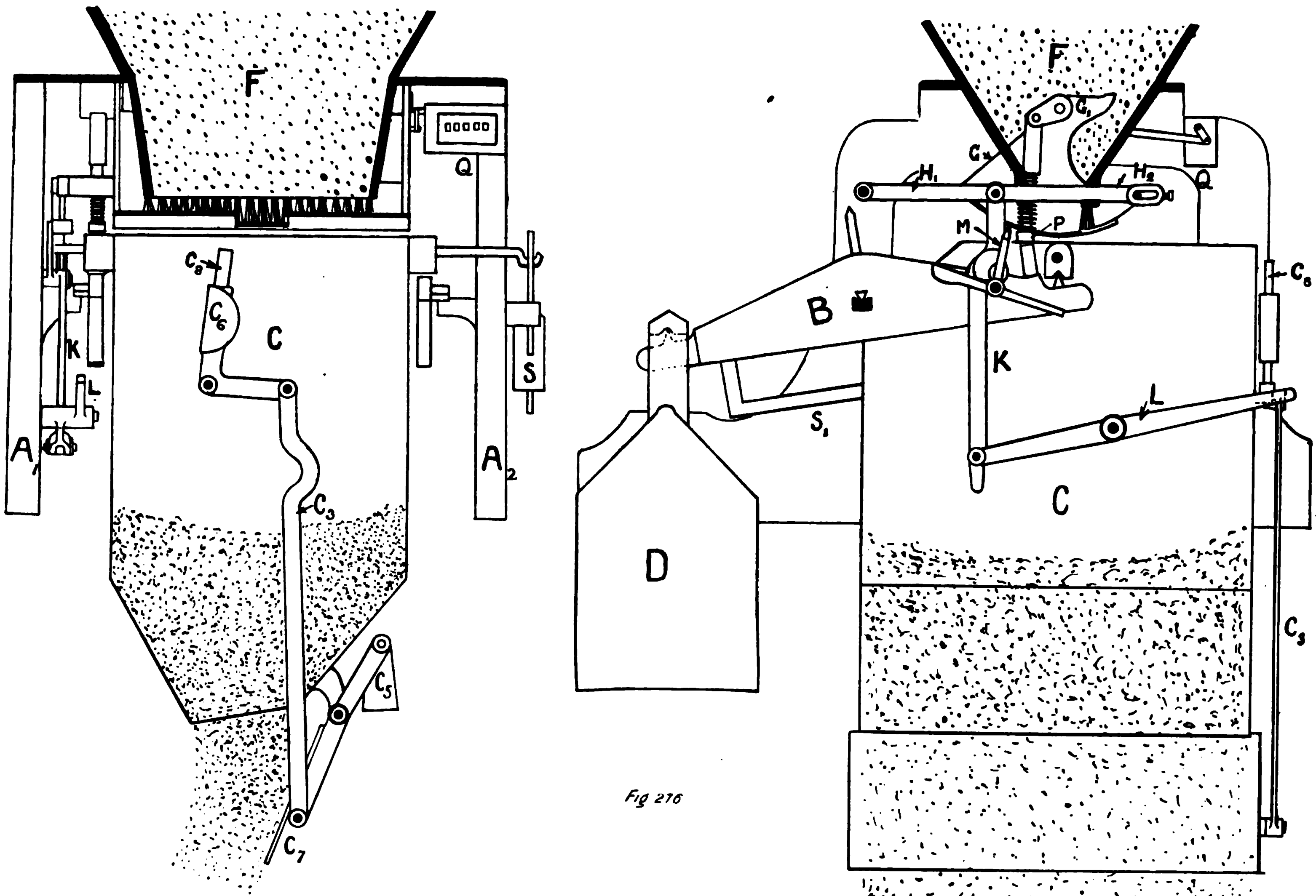



Fig 276

the modern types the crane hook is suspended from the balance arm and the entire load can be put on to the framework when the balance is not in use by throwing over a hand lever which rotates an eccentric passing through a hole in the suspension piece. The general arrangement of the lever system of a crane balance is shown diagrammatically in Fig. 277, while an actual balance of 70 tons capacity is shown in Fig. 278.

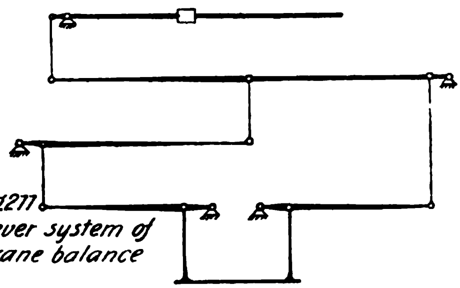


Fig.277 Lever system of crane balance

The multiplication of the lever system is 300. In such balances of large capacity the difficulty met with in the construction is to make the carrying knife-edges sufficiently long to prevent the pressure upon the unit length of knife-edge being too great. In the above-described balance the load is suspended from two levers by means of four suspensions. The levers are constructed of triangular form to give a broad bearing and eliminate any tendency to tilting.

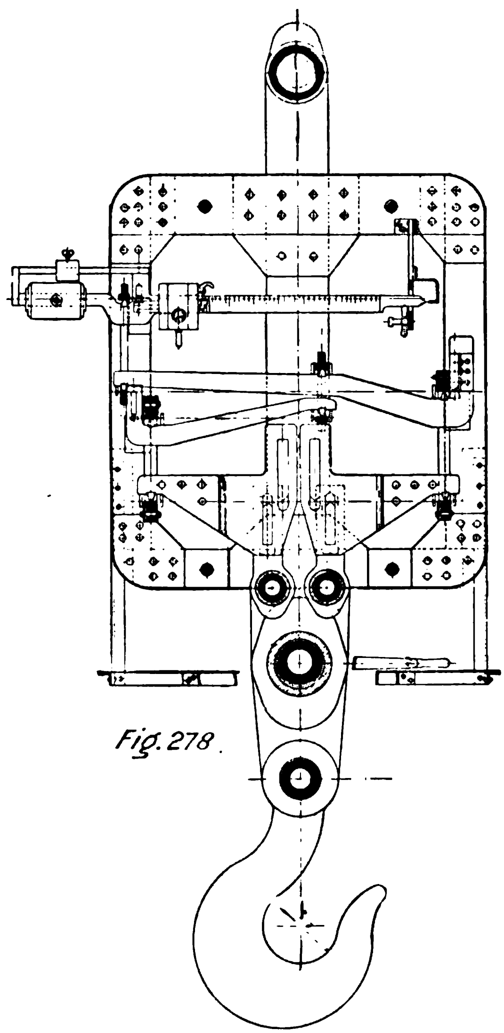


Fig. 278.

*American Locomotive Weigh-bridge.*—The locomotives employed on American railroads are considerably larger than those of any other country, and a weigh-bridge capable of dealing with such loads must necessarily be of massive construction. One weigh-bridge has been built for this purpose and its maximum capacity is 270 tons. This weigh-bridge is probably the argest structure of its type in

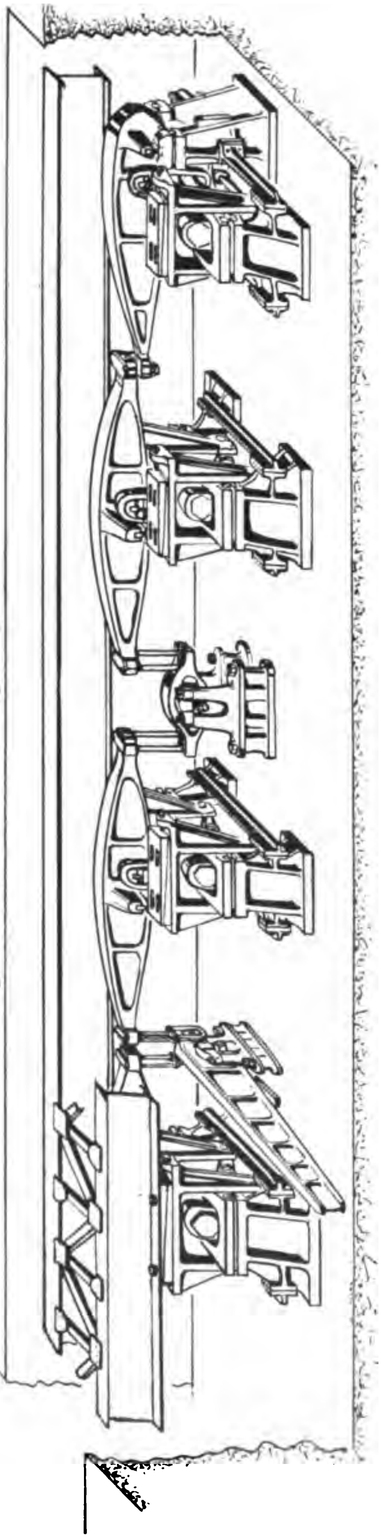


Fig. 279 - 270 ton Locomotive Weigh bridge

existence at the present day. The weigh-bridge is designed with a rigid platform 100 feet long, and in itself weighs 300,000 lb. complete. The lever system is built in the form of two symmetrically arranged parts, each composed of two similar $15\frac{3}{4}$ feet levers and one $12\frac{1}{2}$ feet end extension lever, as shown in sketch (Fig. 279). The weight of the platform is transmitted to these long levers by pairs of short levers set traversely under the girder at six points. The middle levers carry their own load at 8 to 1 leverage, as well as transferring the load from the adjacent lever to the lever on the opposite side. There are in all 70 knife-edges: the maximum load on any knife-edge not exceeding 7000 lb. per linear inch, which is the recognised maximum for American railroad practice. All the beams are made from cast steel, and the knife-edges and bearings from oil-hardened chrome-vanadium steel.

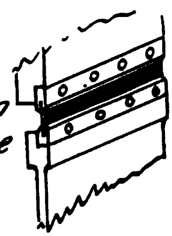
Elaborate precautions are taken to equalise the load along the length of the very long knife-edges necessary for the weight. The lever system gives a multiplication of 200 at the connecting rod to the scale-arm, and with a multiplication of 4 in this arm the total multiplication is 800. The accuracy of this scale is said to be within 20 lb. with the test load of 140,500 or 0·01 per cent approximately.

*Plate Fulcrum Weigh-bridges.*—An interesting form of weigh-bridge has been recently tried by A. H. Emery and the Fairbanks Co. In this weigh-bridge the knife-edges are replaced by thin steel plates bolted rigidly at each end to the

support and lever. The movement of the levers is permitted by the flexing of the plates. A sketch of the construction of one of these fulcrums is shown in Fig. 280. A 50 foot railway weigh-bridge has been constructed on this principle to weigh a maximum of 18 tons. The beam reads to 50 lb.

Fig. 280

Plate fulcrum for weighbridge



The advantage of this plate fulcrum is, of course, the sustained sensitivity, since there is no wear or rusting as in the case of knife-edges; the upkeep costs are also very slight. The use of this plate fulcrum, on the other hand, reduces the possible sensitivity and they must be safeguarded against lateral deflection, such as expansion of the very long levers, since this might result in a permanent distortion of the plates. Practical experience will probably give considerable information as to the value of this device, and if it proves reliable it should certainly find a wide field of application.

## REFERENCES

Bunge. "Beschreibung der Wäge Instrumente Neuester Construction nebsc Constructions Motiven." 1880.

Schlink. "Stabilized Platform Weighing Scale of Novel Design," Tech. Paper No. 106, Bureau of Standards.

——. "Weighing Scales: Principles of Operation of Common Types of Scales and Methods of Inspecting and Testing," *Machinery*, Vol. VII, p. 601. 1915–16.

Edwards, J. D. "A Specific Gravity Balance for Gases," Tech. Paper Bur. Standards, No. 89. 1917.

Taylor, T. S. "Micro-balance for the Determination of the Density of Helium," *Phy. Rev.*, Vol. X, No. 6. 1917.

Pettersson, Hans. "Micro Falance," *Proc. Phy. Soc.* 1920.

Manley. *Phil. Trans. Roy. Soc.*, Vol. CCX. 1910.

Bousfield. "Recent Development in Heavy Track-Scale Construction," Eleventh Annual Conference Weights and Measures, U.S.A.

Walker. "*Theory of a Physical Balance*, Clarendon Press. 1887.

Thiessen. *Travaux et Mémoires du Bur. Int.*, Vol. V, p. 1.

Marek. *Travaux et Mémoires du Bur. Int.*, Vol. III, p. 53.

Poynting. *The Mean Density of the Earth* Publ. Griffin & Co.

Cunliffe and Owen. *Board of Trade Notices Annotated*, Vol. I.

Richartzand Krigar-Mentzel. "Compensated Suspensions," *Zeit fûr Inst.* 1889.

Anderson. "An Electro-magnetic Vacuum Balance," *Trans. Faraday Soc.*, May, 1915.

Urbain. "Vacuum Micro-balance of the Electro-magnetic Type," *Comptes Rendus*, Vol. VI, 347. 1912.

Arndt. "Gas Balance," *Chem. and Metall. Engineering*, p. 291, March 15th, 1919

——. "Direct Reading Density Balance for Solids," *Journ. d. Phys.*, Vol. VI, p. 291. 1916.

——. "New Assay Balance," *Met and Chem. Eng.*, Vol. XIII, No. 8. Aug., 1915.

Shakespear. "Note on some Modifications in an Ordinary Balance which conduce to Ease and Quickness of Weighing," *Phil. Mag.*, Vol. XXVII, p. 990. 1914.

Ayrton, Mather and Smith. "Current Balance," *Phil Trans. Roy. Soc.* 1908.

P. L. du Nouy. *Journ. of General Physiology*, Vol. I, No. 5. May 20th, 1919.

Rayleigh. "The Principle of Similitude," *Nature*, Vol. XCV. March 18th, 1915, pp. 66–68.

*Automatic Coin-Weighing Machines.*

"Cotton and Pilcher's Coin-Sorting Machine for the London Mint," *Bull. d'Encouragement*, p. 187. 1870.

"Coin Balance of Great Sensibility," *Bull. d'Encouragement*, p. 164. 1870.

Seguiers. "Coin Balance," *Moniteur Industriel.* 1875.

——. *Polyt. Central Paper*, p. 1533. 1858.

Hartig. *Official Report of the German Empire concerning the Universal Exhibition at Vienna.* (Detailed description of Ludwig Seyss' Balance.) Vol. II, No. 1. 1873.

# CHAPTER VII

## THE MEASUREMENT OF WORK

THE present chapter deals with the various types of indicators and dynamometers which have been devised for the measurement of power. Their greatest field of application is in the determination of the energy output of prime movers and in the testing of the efficiency of machine tools and gear transmission. The output of prime movers is generally rated in horse-power units. The origin of this unit as a measure of the activity of machinery is due to Thomas Savery, the inventor of an early type of steam engine.

James Watt adopted the same term for rating the output of his steam engines, but the value of his unit in foot pounds second units was six to eight times as great as Savery's.

It is a curious fact that the horse-power unit of Watt, based as it is on the British Standards of a *foot* and a *pound*, should have become a standard in countries which have never accepted these primary units for the measurement of length and mass.

*Definition of the Horse-power Unit.*—A century and a half ago James Watt and his business partner, Boulton, determined the value of their horse-power unit in terms of the gravitational units as follows :

Some heavy horses of Barclay and Perkin's Brewery, London, were caused to raise a weight from the bottom of a deep well by pulling horizontally on a rope passing over a pulley. It was found that a horse could raise a weight of a 100 lb., while walking at the rate of 2·5 miles per hour. This is equivalent to 22,000 foot pounds per minute. Watt added 50 per cent to this value, giving 33,000 foot pounds per minute, or 550 foot pounds per second. The addition of 50 per cent was an allowance made for friction, so that a purchaser of one of his engines might have no cause of complaint.

The figure thus arrived at by Watt is admitted to be in excess of the power of an average horse for continuous work, and is probably at least twice the power of the average horse working six hours per day.

The value 550 foot pounds second was given by Watt without consciousness of the distinction between standard and local pounds weight. To give the horse-power unit an absolute value it is necessary to specify the unit of force with greater exactness, and this can most readily be effected by defining the horse-power in terms of the electrical unit of power, which is an absolute one.

The relation between the electrical unit of energy—the watt—and the horse-power unit can be arrived at by the following considerations:

A watt is $10^7$ times the work of an erg per second. An erg is a dyne acting through one centimetre (0·3937 in.). A dyne is a force which gives a gramme an acceleration of a centimetre per second per second.

A standard foot pound per second is the work done per second by a force of a standard pound acting through a foot. A standard pound is a force which gives a pound (453·59 grms.) an acceleration of 981·19 cms. per second per second. Hence there are

$$\frac{746 \times 10^7 \times 0 \cdot 3937}{981 \cdot 19 \times 453 \cdot 59 \times 12} = 550 \cdot 0$$

standard foot pounds per second in a horse-power.

On account of the variation with $g$[1], and because the equivalents of the horse-power are not decimal multiples of any of the fundamental units, and further because its definition and value are different on the Continent of Europe from its definition and value in England and America, it has been long felt that the horse-power is an unsuitable unit for many purposes. Modern engineering practice is constantly tending away from the horse-power and towards the watt and kilowatt. Particularly in electrical engineering is this the case. Here a definite action has been taken to eliminate the horse-power entirely as a unit of power. At the International Electrotechnical Commission in Turin, Italy, in September, 1911, it was decided that in all countries electrical machinery, including motors, would be rated in kilowatts only.

## I. Indicators

The power of reciprocating engines is generally calculated from the area of the graphical diagram representing the pressure-distance curve for each piston and cylinder. The first instrument for effecting this appears to be due to Watt and Southern, and its simplicity will be gathered from Fig. 281. The indicator has a vertical brass cylinder

[1] Value of $g$ at London = 981·19 cm. per $(\text{sec})^2$
" " Equator = 978·02 " "
" " Pole = 982·21 " "

1·13 in. diameter (one square inch area) fitted with a piston, the upper extremity of the rod of which is provided with a pencil. The piston is connected with the top of the indicator cylinder by a helical spring, so that any variation in the pressure below the piston will lengthen or shorten this spring, and thus cause the height of the piston to be a measure of the pressure below it. The lower end of the indicator cylinder is placed in communication with one end of the engine cylinder, so as to measure the varying pressure during the stroke. The motion of the paper in their tests was usually obtained from a point in the bridle-rod of the parallel motion; the return movement being given either by string connected with a helical spring or by a weight.

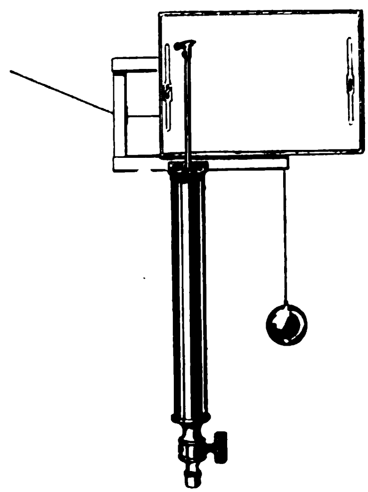


Fig. 281
Watt's Indicator

At the low steam pressure employed by Watt, the connection between the indicator and the cylinder could be made throughout by taper sockets and plugs.

Fig. 282
Richards' Indicator

Although the Watt indicator was later improved and fitted with the well-known drum in place of the card by John MacNought about 1825, the instrument remained for many years essentially in its original form, and the modern design of indicator appears to be due to Prof. C. B. Richards, who introduced the indicator bearing his name about 1862. (See Fig. 282.)

The great improvement it embodied was the employment of a multiplying arrangement by which the stroke of the indicator piston is reduced and the distortion of the diagram, through the inertia of the moving parts of the instrument, was greatly reduced. The capacity and convenience of the apparatus was also improved in other respects and all the instruments since introduced have followed the methods that Richards originated.

The instrument consists of a small cylinder containing a piston held

by a spiral spring. A drum is also provided to carry the paper on which the diagram is to be drawn, as in MacNaught's instrument, but the paper arm is some little distance from the cylinder. Round the cylinder is fitted a collar with two projecting arms which support the two fixed points of a Watt's parallel motion. The parallel point of this motion carries the pencil and the piston is connected with one of the bridle-rods at the point that has only one-fourth of the motion of the pencil. By this arrangement the pencil can be swung round to be in contact with the paper just when desired whilst the instrument is in action; this is a feature of the greatest practical importance.

C. H. Crosby about 1880 reduced the inertia of the indicator still further, adapting it for use with high speed engines.

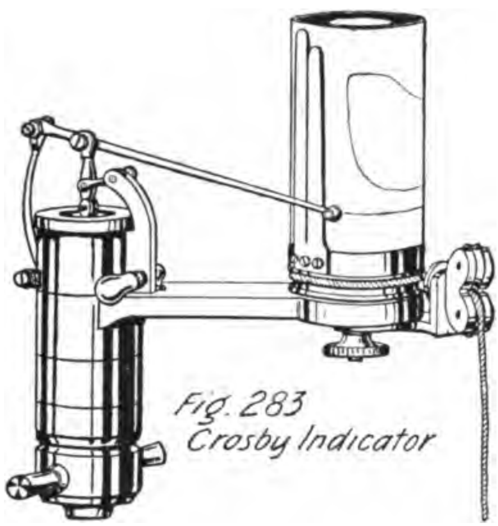


Fig. 283
Crosby Indicator

The Crosby indicator is shown in Fig. 283. The link work is slightly different from the Richards, but gives the usual linear motion to the pointer. The magnification of the levers is six times.

The piston of this indicator has an area of half a square inch and works in a steam jacketed cylinder. To avoid the twisting action of the springs these were made double and attached to the piston by means of a ball and socket.

Darke introduced in this country at about the same time as Crosby, an indicator in which he used a simple lever working in slots with a magnification of four times. Darke's chief contribution, however, is his detent device, which has since been largely adopted. This consists of a pawl which can be allowed to engage in the teeth of a ratchet-wheel cut in the base of the drum carrying the paper and so stop its rotation by preventing its return under the action of the spring when the cord slackens.

The introduction of superheated steam and the rapid development of internal combustion engines involved still further modifications in the indicator in order to remove the springs from the region of high temperature.

Wayne, Crosby, and others have designed instruments in which the

springs are fixed above the cylinder. The simple design due to Wayne is shown in Fig. 284.

The ordinary helical spring is replaced by a bow-spring situated outside the cylinder away from the action of the steam. This can be easily removed and replaced, as its ends simply fit into grooves provided in the top of the extended piston rod and a fixed piece above it. It is retained in position by a small spring pin in one of the grooves engaging with a notch. The piston is 0·5 sq. in. area and its travel is magnified four times by the pencil mechanism, which consists of a pantograph combination of levers.

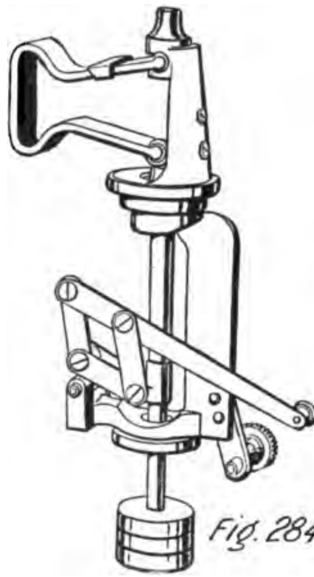


Fig. 284

Wayne also invented a neat form of indicator which almost reverts to the simplicity of Watt's instrument in its essentials. In this instrument a semi-rotary piston is employed to actuate the pencil arm without the intervention of any link-work, as shown in Fig. 285.

The piston consists of a diametral plate, capable of working steam light within a cylindrical chamber having two fixed abutments, on opposite sides of which are inlet and outlet ports. The indicator spring is of the double helical type, but works in torsion and resists or measures the action of the steam by checking the rotation of the piston. The outer end of this spring is secured in a groove on the axle of the piston, while the inner end terminates in a brass plate having two holes fitting upon steel pins which project from the cylinder cover, which allow the spring to shorten as the torsion is increased. To the opposite end of the piston spindle the arm carrying the pencil is secured and, to allow for the circular path it describes, the diagram paper is held as a cylindrical surface by circular clips concentric with

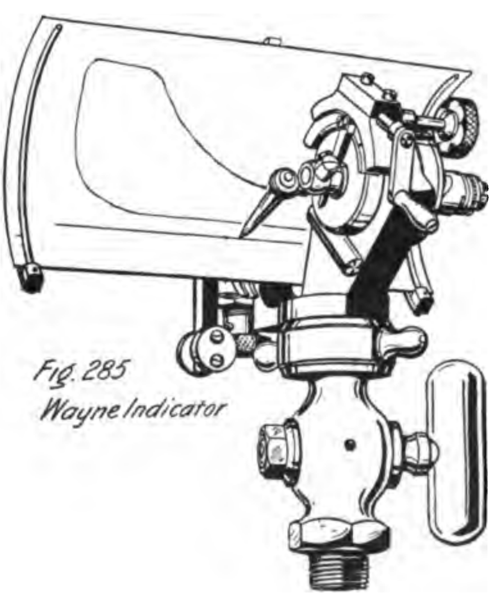


Fig. 285
Wayne Indicator

the piston axis and attached to an aluminum sliding frame. A string secured to one end of this frame imparts the reduced motion from the engine piston and the return motion is obtained by a spring barrel. In some cases instead of the usual pencil, a hard steel tracing-point is employed, marking on black-faced paper.

To enable this instrument to obtain a diagram from an engine of exceptionally high speed, without the usual distortion due to the inertia of the moving parts, it is provided with an apparatus for taking the diagram in such cases in layers or "lines." This attachment, which can be secured to a horn projecting from the cylinder, consists of a segment of a worm wheel with a screw operated by a winch handle, and a steel tongue passing through a slightly elongated hole in the piston axle. By

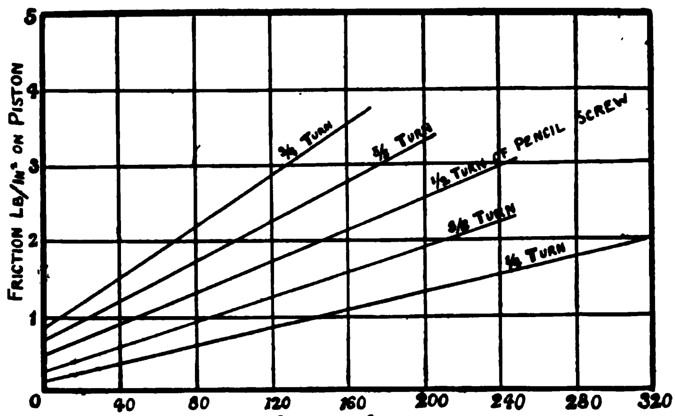


Fig. 286

these means the rotation of the piston is limited to the amount resulting from the backlash in this hole, so that the pencil moves only through a small portion of its ordinary angular travel; but by turning the worm wheel slowly throughout its range, the series of layers are placed together in a way that gives a complete average diagram free from vibration disturbances.

*Errors of Pencil Indicators.*—The inaccuracy of indicator results may be due to two causes:

(*a*) The pressure indicated may be affected by inertia or by friction in the instrument.

(*b*) The motion of the drum may not synchronize with that of the engine on account of the stretching of the string or straining of the reducing gear.

Of the instrument errors, the inertia of the parts is generally a fixed quantity determined by the design and construction of the indicator,

and the observer can therefore only minimise it by selecting the lightest and most rigid type consistent with his requirements.

All instruments show slight backlash in the pin joints, but this should be kept small by periodical attention to the taper pins forming these joints. The friction of the pencil on the paper is a very serious source of error in accurate work.

Stewart conducted experiments on a Crosby Indicator and found, by allowing the indicator system to oscillate, that the frictional force varied, as shown in Fig. 286. The pencil employed was a 5 H. Koh-i-Noor lead rubbing on smooth, dry matt paper.

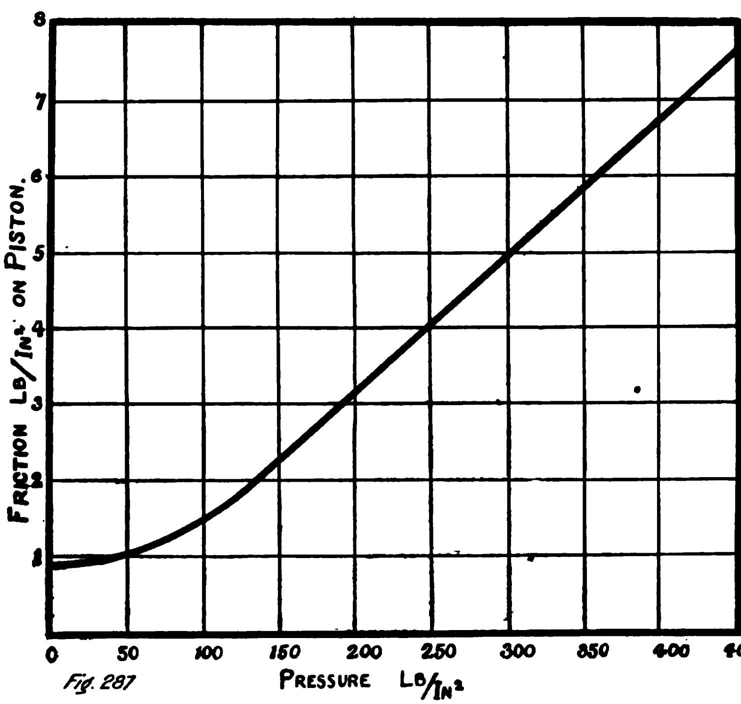



Fig. 287

The same investigator also found that the friction varied with the height of the pencil, that is with the pressure in the cylinder. This effect is illustrated in curves shown in Fig. 287. The readings were taken with three-eighths turn of the pencil adjusting screw and a 400 spring. It will be observed that the friction is almost proportional to the pressure after about 100 lb./sq. in.

The second source of error referred to above, due to the connecting gear, was first investigated by Osborne Reynolds, who in consequence abandoned cord in his experiments in favour of connecting rods. The magnitude of the stretch of the cord has been determined for a standard

outfit by Stewart. This is for the case of an indicator drum having the following characteristics :

Pull of drum spring = 1·47 kg. rate 0·14 kg. per cm. : friction of drum 0·17 kg. : equivalent mass of drum 100 gms. at surface ; length of diagram 3·92 cm.; speed of engine 540 r.p.m. ; and crank to connecting rod ratio 1–5. The cord used was Crosby cord, 4 ft. long, previously stretched by hanging a weight of $8\frac{1}{2}$ lb. to it for twenty-four hours.

In Fig. 288 the stretch is plotted in millimetres, and it will be observed that this distortion of the diagram is a very variable correction depending on the inertia of the drum, strength of the spring, the friction of the drum on its spindle and the speed of rotation of the engine.

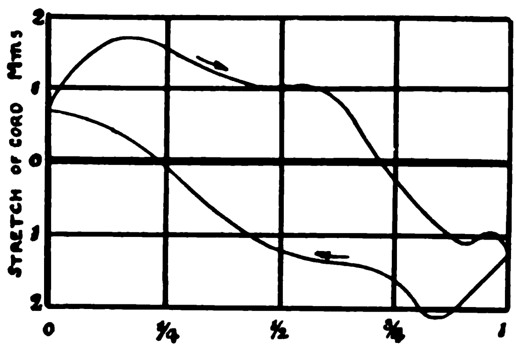


Fig. 288

The modern tendency in the design of indicators especially, for research work, is to employ optical magnification, since by this means the backlash of the link-work is eliminated and the inertia effects are also reduced.

Professor Hopkinson's indicator has the usual type of piston, but the spring is in the form of a beam clamped at both ends, whose deflection is communicated to a small tilting mirror. The instrument is shown in section in Fig. 289.

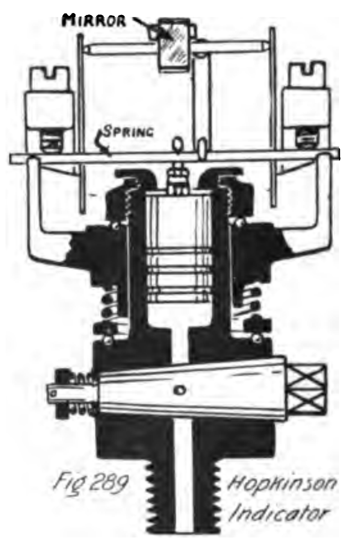


Fig 289 Hopkinson Indicator

The body of the indicator screws on to the cylinder cock. The piston is made hollow, but closed at each end, and the piston rod is held in engagement with the beam-spring by a hooked wire, thus giving the piston lateral freedom. The motion of the piston and spring is transmitted to the mirror by a light steel strip, and causes a tilt of the mirror in a vertical plane. The mirror spindle is fixed to the frame, which is free to rotate about the body of the indicator, and this movement is controlled by rods connected to the crosshead or other part of the engine.

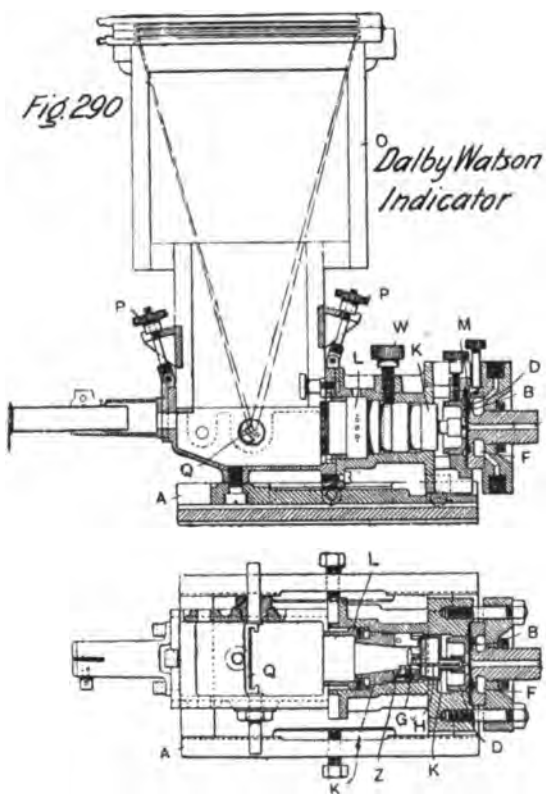
When a beam of light is projected on to the mirror the reflected beam

therefore undergoes two deflections: a vertical displacement due to the pressure and a lateral displacement due to the connection with the engine piston. The beam of light is focussed on to a glass screen on which the diagram may be observed as a bright line, or the screen may be replaced by a photographic plate when a permanent record is desired.

The Hopkinson indicator requires somewhat careful assembling since the spring supports are liable to introduce considerable friction when the spring is deflected, and for this reason a strong spring should always be used to make the working range of the deflection small. There is also a slight error due to the fact that the screen is not curved.

It is more usual in the case of optical indicators to abandon the use of the piston as well as the link-work and employ a flexible steel diaphragm, a modification first suggested and used by Professor Perry. A good example of this class is the instrument designed by Dalby and Watson and developed by Cussons of Manchester. The principle of this optical indicator will be understood from Fig. 290.

Fig. 290 Dalby Watson Indicator




The indicator has two mirrors, one of which is rotated about its axis by the movement of a diaphragm under the action of the fluid pressure, while the other is rotated about an axis at right angles to the former by a reciprocating part of the engine; records of the pressures being made upon a photographic plate by means of a ray after reflection from both mirrors. The necessary adjustment of the line corresponding to atmospheric pressure when the diaphragm is changed is effected by altering the position of the mirror; the position of the diaphragm being unaltered. There is also provided an adjustable stop at the back of the diaphragm, and means whereby an accumulation of liquid in contact with the

diaphragm is prevented. The whole of the indicating apparatus is mounted on a rigid base plate $A$, adapted to be securely fixed to the engine. The diaphragm $B$ is placed in communication with the engine cylinder through the pipe $C$, a stop $D$, adjustable by screwing relatively to the framework $A$, is provided at the back of the diaphragm, the stop being adapted to bear against the diaphragm along the circumference of a circle and to be fixed in any given position by means of a set screw.

A water-cooling chamber $F$ is provided in the neighbourhood of the diaphragm. The diaphragm is connected to the pivoted mirror $G$ by means of a rod $H$, and in order to alter the adjustment of the line corresponding to a given pressure, such as atmospheric pressure, the mirror is moved relatively to the diaphragm by rotating the piece $K$ by means of a tommy bar inserted into one of the apertures $L$. This piece $K$ carries the mirror $G$, and its movement in the longitudinal direction relative to the rod $H$, which is held steady by the diaphragm, causes the mirror to tilt to give the necessary adjustment. A drain hole $M$ is provided in the space in front of the diaphragm, this hole being normally closed by means of a screw which can be withdrawn in order to remove oil or other liquid from the front of the diaphragm. The camera is mounted on the apparatus so that it can be readily removed by loosening the catch screws $P$. The pivoted mirror $Q$ is actuated in any suitable manner from the piston of the engine, and in any desired phase relationship with the movement of the piston.

The operation is as follows :

The lens and mirror are adjusted so as to give an image of the source of light on one of the apertures $R$. This image is focussed by means of the concave mirror $G$, and the plane mirror $Q$ on to the ground glass screen of the camera, which can be replaced in the usual manner by a sensitive plate. The mirror $Q$ is given a movement corresponding with the movement of the piston of the engine by any suitable means, the driving mechanism of the mirror including an epicyclic device, whereby the phase can be altered to give any desired difference of phase between the movement of the mirror and the movement of the piston of the engine. A diaphragm suitable to the pressures to be recorded is fitted into the apparatus and the position of the mirror $G$ adjusted by rotating the piece $K$. The pressure in the cylinder acts on the front of the diaphragm $B$, causing this to tilt the mirror $G$ in such a manner as to cause a spot of light to move on the ground glass or sensitive plate in the direction at right angles to the paper. The motion of the mirror $Q$, imparted from the engine piston or other reciprocating part of the engine,

causes the spot of light to move over the ground glass or sensitive plate in the direction parallel to the paper. It will thus be seen that the pressure diagram is produced on the ground glass or on the plate, corresponding with the pressures in the cylinder at different points of the stroke of the piston of the engine. In order to keep the diaphragm cool, water may be supplied continuously through the chamber *F*.

The restoring force on the diaphragm is due to its own elasticity, and it is important therefore that it should not be subject to fluctuations in temperature which would introduce a correction for the temperature coefficient of an uncertain amount. The deflection of a diaphragm indicator as a rule is not directly proportional to the pressure applied,

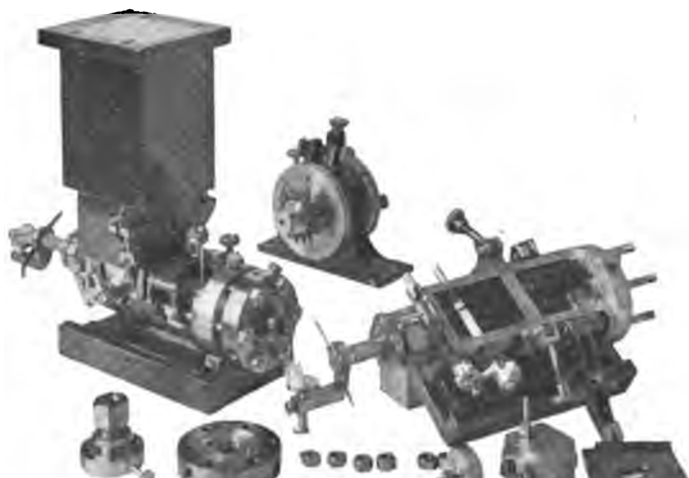


*Fig. 291*

and the planimeter cannot be employed for the determination of the mean ordinate.

A very simple diaphragm indicator which deserves mention in passing is that devised by Professor R. H. Smith some years ago. The instrument is shown in section in Fig. 292. The diaphragm is of hard copper $\frac{3}{4}$ in. diameter with a maximum motion of one-twentieth of an inch. A circular plate of steel forms the spring and the magnification is affected by 20 to 1 lever. This lever is made of steel tube without pin joints, the butt end being cut and turned down to connect with the diaphragm. Another strip leading out from the end of the tube is clamped to the support on the indicator body. The diagram is traced by a small ink-pen, which is not in actual contact with the paper, but projects the ink out in a fine stream under centrifugal pressure caused by the oscillating motion of the lever.

The future development of the high-speed indicator will probably be based upon the use of electrical phenomenon, such as the Piezo effect. It is well known that certain crystals, notably quartz and tourmaline, when submitted to pressure between two metallic surfaces show an electric charge of opposite sign proportional to the pressure at these surfaces. The development and variation of the charges with changes of pressure appear to be instantaneous, and any lag is due solely to the recording electrical instrument employed. A short period string electrometer can be adapted to follow the variations in the magnitude of the electric charge without appreciable time lag. Inertia and friction would of course be practically insignificant with this method.

Sir J. J. Thomson has obtained some very interesting results with gun-

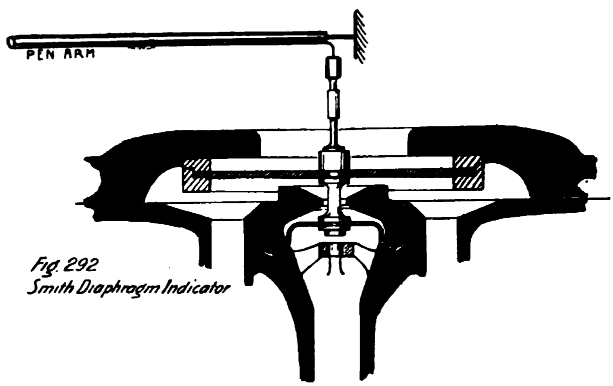



Fig. 292
Smith Diaphragm Indicator

powder explosions which indicate the possibilities of the method for investigating explosion waves generated in very short time intervals.

The above principle has also been applied to the design of an accelerometer by the late Prince Galitzin in Russia, and his instrument has proved to be eminently suitable for seismological purposes.

*Ergometers.*—The indicators already dealt with estimate the work done in each individual stroke of the engine. Several instruments have, however, been devised for integrating the work over a long period. Morin, Ashton, Storey, and others have used a disc and roller arrangement similar to the water meter described on page 78. A disc rotates on its axis at a rate proportional to the engine speed or the distance moved through by the point of application of the force. A small roller in contact with this disc slides radially so that its position from the centre is always proportional to the pressure or force acting.

The revolutions of the roller are proportional to the product of distance and force and thus measure the work done. Dr. C. V. Boys has designed

an instrument termed the "Boys' Ergometer," which depends upon a novel principle. He employs a planimeter wheel, the plane of which is inclined at an angle to the horizontal proportional to the pressure. This wheel rolls on a surface, moving backwards and forwards along a horizontal line by means of reducing gear connected with the crosshead of the engine. If no slipping takes place the wheel will be displaced laterally on the paper, so that its height on the surface above a given datum line is proportional to the travel of the surface multiplied by the tangent of the angle of inclination. Thus the displacement of the wheel can be made to record the work done.

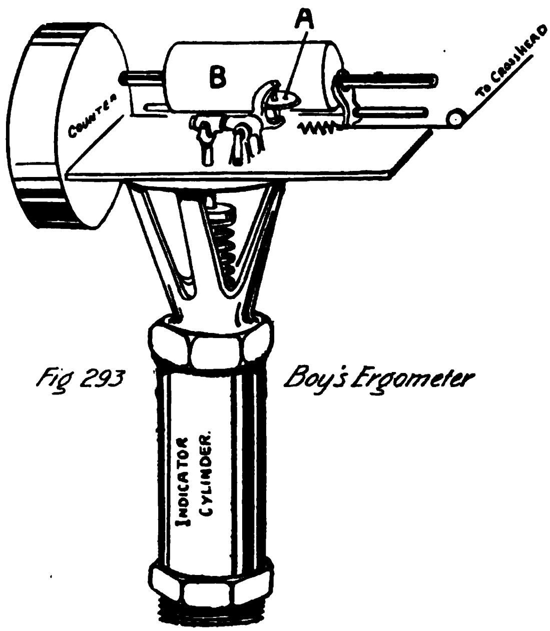



Fig 293 Boy's Ergometer

In Boys' practical realisation of this principle of integration, the wheel $A$ is fixed on an axis above the indicator cylinder (Fig. 293), and the reciprocating surface is a sliding drum $B$ connected to the crosshead by the usual cord and reducing gear. The inclination of the wheel $A$ is varied by the displacement of the piston rod and causes the drum to rotate when sliding backwards and forwards. The drum rotates the spindle of the counting gear contained in a box at one end. Hence the reading of the counter is the sum of the areas of all the indicator cards in a given time interval and so is a measure of the total work done. Further, the average horse-power can be obtained by dividing the reading by the time interval.

## II. Transmission Dynamometers

The term transmission dynamometers is applied to that type of instrument which measures the energy transmitted with negligible or very small loss in the form of friction and the generation of heat.

There are numerous ingenious forms of instrument belonging to this class which are generally used for testing machine tools, etc., but only a few representative types can be described here.

*Belt Dynamometers.*—Froude's belt dynamometer measures the difference in tension of the two sides of the driving belt connecting the motor to the machine under test.

The belt employed for transmitting the power is passed over two jockey pulleys $A$ and $B$ on either side of the driving pulley $C$, as shown in Fig. 294.

The jockey pulleys are mounted in a frame pivoted at its mid-point $D$; a spring balance measures the force tending to tilt the frame. If

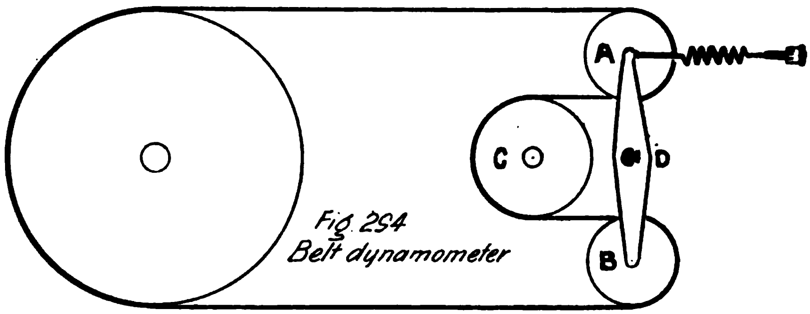



Fig. 294
Belt dynamometer

all the belts are parallel to the axis of the spring balance it is evident that the pull on the spring is equal to twice the difference in the tension of the belt on the tight and slack side respectively.

The difference in tension of the two sides of the belt multiplied by the linear speed of the surface of the driving pulley at that instant gives the rate of doing work, or, if appropriate units are used, the horse-power transmitted.

Froude constructed his dynamometer with a recording device consisting of a drum rotated by the jockey pulley. This drum carried a continuous roll of paper on which a record of the force was made by a pencil connected to the spring balance. The jockey pulleys were mounted to run very freely to reduce friction losses and the oscillations of frame damped out by an oil dashpot.

This recording arrangement measures the distance travelled by the driving belt, and is therefore in error by the amount of the slip of this belt on the driving pulley. It would be preferable therefore to use the driving pulley for the purpose of rotating the recording drum.

A belt dynamometer which is very simple in application is that attributed to Alteneck. The belt in this apparatus is drawn together between the driving and driven pulleys by jockeys mounted in a pivoted frame, as shown in Fig. 295. The component of the difference in tension in the two sides of the belt is counterbalanced by a weight hanging on the end of an arm.

It can be easily shown, if the frame is symmetrical about the centre line of the pulleys, that

$$T_1 - T_2 = \frac{R}{(\sin \alpha + \sin \theta)}$$

and the work done is equal to the linear speed of the pulley rim multiplied by this quantity.

Other forms of belt dynamometers have been devised by various

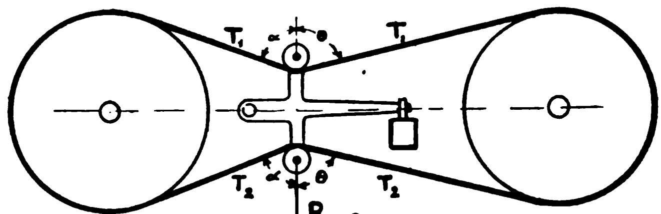



Fig. 295 Belt dynamometer

investigators for special application, notably by Boys, Parsons, Tatham, King, and Farcot.

*Gear Dynamometers.*—It is possible to construct a very compact form of transmission dynamometer by the use of the reactions in a train of gears. This form is not widely used owing to the somewhat high friction losses that it entails and the cost of manufacture. The principle of the method will be illustrated by describing the simplest form (Fig. 296). The gearing employed is of the bevel differential type. The driving pulley $A$ drives the pulley $B$ in the opposite direction through the bevel mounted on the weighing beam. The reaction on the bearing of this wheel is equal to the tooth pressure, hence the driving force at the rim of the pulley is equal to the dead weight on the end of the beam divided by the ratio of the length of the arm to the radius of the pulley. In passing it might be remarked that the Lanchester gear tester, described on page 313, involves this principle in a more highly developed form.

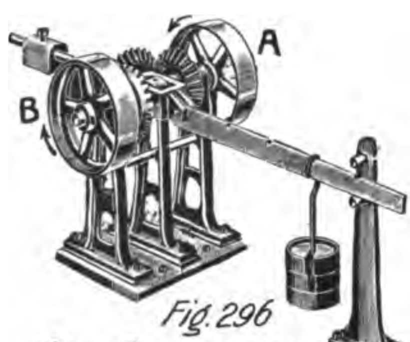



Fig. 296 Gear Dynamometer

*Torsion Dynamometers.*—Appliances which measure the power transmitted by estimating the torsional deflection of the driving shaft are largely used in marine work. The long propeller shafts of steamships make the method particularly easy of application.

If the angular deflection ($\theta$) of the shaft is determined at any instant, then the torque $T$ in inch pounds is given by

$$\theta = \frac{32TL}{K\pi d^4} \text{ for a cylindrical shaft,}$$

and $$\theta = \frac{2TL}{K\pi(d^4 - d_1^4)} \text{ for a hollow shaft.}$$

Where $L$ = length of the shaft, in inches, between the two points where deflection is measured

and $K$ = modulus of rigidity in millions of pounds per square inch. (For steel $K$ is about 12,000,000 lb. per square inch.)

$d$ and $d_1$ = outside and inside diameter of the shaft in inches.

The horse-power is found by the usual formula :

$$H.P. = \frac{\pi NT}{198{,}000}$$

where $N$ = number of revolutions per minute.

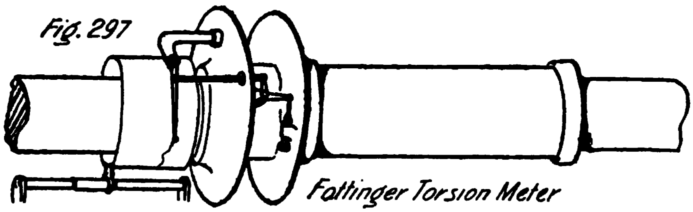
In view of the uncertainty in the value of $K$ and the difficulty of calculating the value of $\theta$ in radians from the empirical reading of an instrument it is preferable to calibrate the apparatus in position and determine the instrument reading for known values of torque applied to an arm clamped to the stationary shaft. This method of calibration is particularly useful when the length of shaft utilised is broken by a coupling, since the influence of this discontinuity is difficult to allow for in a calculation of the coefficient.

The torsion dynamometers described in the following pages differ considerably in their mechanism for indicating the deflection ; some of the types being applicable for low speeds, whilst others, such as some forms of optical indicators, are more convenient for use with high-speed shafts.

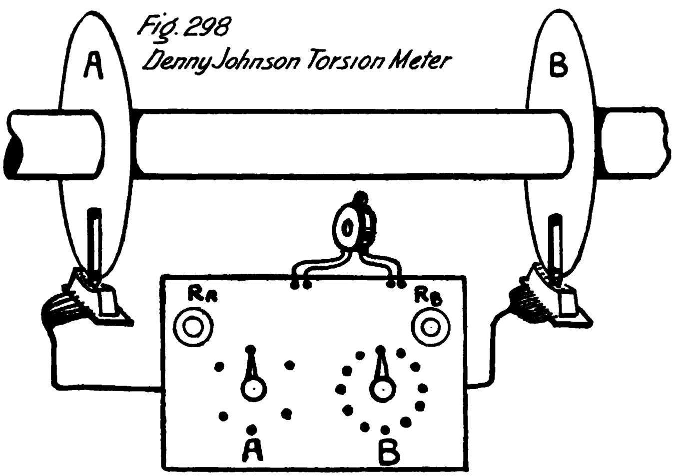
The Fottinger dynamometer employs a simple lever system which records the torque on a drum revolving concentrically with the shaft, but at a definite fraction of its speed. The mechanism of the instrument is mounted on two flanges, one of which is fixed to the shaft, whilst the other is carried on a tube which is fixed to the shaft only at its extreme end, as shown in Fig. 297.

The twisting of the shaft within the sleeve causes a relative movement of the flanges, and this is magnified twenty-seven times by the levers connected to the tracing-point. The recording drum is driven by sun-and-planet gear at about one-quarter speed, so that one complete diagram gives the torque during four revolutions.

This dynamometer was first used by Fottinger in an elaborate series of experiments on German merchant ships, in course of which horse-powers up to about twenty thousand were measured.




Messrs. Archibald Denny and Charles Johnson have devised several forms of torsion dynamometers and have conducted experiments with them extending over many years. They at first endeavoured to measure the angle of deflection of a shaft by using two insulated discs, at a distance apart, which were fitted with contacts at a point on the periphery of each. These contacts were arranged to touch two tongues simultaneously once in each revolution, and the traverse movement which it was necessary to give to one tongue to maintain synchronous contact when power was being transmitted, was a measure of the angle turned through. This device, although quite satisfactory at low speeds of about 100




R.P.M., proved unsatisfactory at high speeds and was abandoned in favour of an electromagnetic induction method.

This instrument was also provided with a traversing screw setting, but this feature was afterwards developed into the form shown in Fig. 298, in which all the setting could be effected from a remote point away from the disturbing noise of the machinery, which made the use of a

telephone somewhat difficult. There are fixed at a suitable distance apart, two light gun-metal wheels $A$ and $B$. On each wheel is mounted a permanent magnet, the projecting pole of which is made V-shaped in order to produce an intense and magnetic field at the point. Underneath the magnets, and set concentrically with the wheels and shaft, are fixed two inductors, each of which consists of a quadrant-shaped piece of soft iron carried on a gun-metal stand provided with suitable levelling screws. On each piece of iron are mounted a number of separate but similar windings of insulated wire, there being a certain suitable number of windings per unit of circumferential length of the iron. There is in conjunction with the inductors a recording-box, in which are mounted two series of contact-studs, around which scales are fixed. In connection with the series of studs, two contact-arms $A$ and $B$ are arranged, by means of which electrical connection may be made at will between any desired stud of a series and its contact arm. There is in series $A$ a stud for every separate winding in the inductor $A$, and in series $B$ a stud for every separate winding in the inductor $B$, each stud being connected to its particular winding by means of a separate wire, all the wires being contained in the multiple cables. The remaining ends or returns of the winding on the inductors are all connected by means of two common wires (also contained in the cables) to the contact-arms $A$ and $B$ respectively.

Included in each of these two circuits is a variable resistance (by means of which the strength of the current flowing in the circuit may be adjusted as desired), and one winding of a differentially-wound telephone receiver. The scale $A$ is divided into six equal parts, there being six separate windings in the inductor $A$, and thus six studs in the series $A$; the length of five subdivisions of the scale thus represents the circumferential length occupied by all the windings on the inductor, each subdivision representing the distance between neighbouring windings, which is usually 0·2 in. The scale $B$ is divided into fourteen equal parts, there being fourteen separate windings on the inductor $B$, and thus fourteen studs in the series $B$. The length of thirteen subdivisions of the scale, as before, represents the circumferential length occupied by all the windings in the inductor, the distance between neighbouring windings being represented by one subdivision of the scale; the usual distance between neighbouring windings in the inductor $B$ is 0·02 in.

To facilitate the accurate and easy setting of the magnets above their respective windings, lines are cut in the tops of the inductors exactly above the end windings, and the magnets are set to these lines. When the shaft rotates without transmitting power, a current of electricity

is induced in the end or zero winding of each inductor, the contact-arm being first placed in contact with the end or zero stud in each series. These two separate currents both transverse their respective circuits, passing in each case from the inductor winding in which they are induced to the respective zero studs to which these windings are connected, thence by way of the respective contact-arms, resistances, and telephone receiver windings back to the inductors again. The connections to the receiver windings are so arranged that the effects of the two separate currents flowing therein are in opposition and thus neutralize each other's effect on the receiver when the strengths of the two current flowing are exactly equal at the same instant. By means of the variable resistances in each of the circuits the currents are made equal in strength, and then so long as the shaft transmits no power, and is thus subject to no torsion, no sound will be heard on listening at the receiver, since the currents induced in the zero windings of the inductors have been equalised, and are both induced at exactly the same instant. When transmitting power, the shaft is subject to a certain torsion or twist, which causes the zero winding of the inductor next the turbine or engine to be excited in advance of the other by the amount of the torsion of the shaft; a loud ticking sound will then be heard in the receiver, as the currents no longer neutralize each other.

Contact-arm $B$ is then shifted from stud to stud, until the position of greatest silence in the receiver is once more obtained. When this position is found, the reading on the scale $B$ opposite the contact-arm represents the circumferential measurement of the angle of torsion of the shaft at the radius of the inductor windings. A current equal in strength at the same instant to that induced in the zero winding of inductor $A$ is now being induced in that winding of inductor $B$, which is in connection with the contact-arm $B$; the scale reading thus represents the displacement of one magnet with regard to the other due to the torsion of the shaft. In the event of the torsion being found to be too great to be measured on scale $B$ alone, contact-arm $A$ is shifted from stud to stud until a reading can be obtained on scale $B$, the torsion reading being equal to the sum of the readings on scale $A$ and $B$. The reading corresponding to any large displacement of one magnet relatively to the other is thus easily obtained by the combined use of the scales $A$ and $B$. The recording box is usually placed in a quiet cabin, while the sound in the telephone is quite definite, for fine adjustments it is desirable to have as little extraneous noise as possible. The torque can be calculated from the dimensions or a separate calibration by the usual methods previously described.

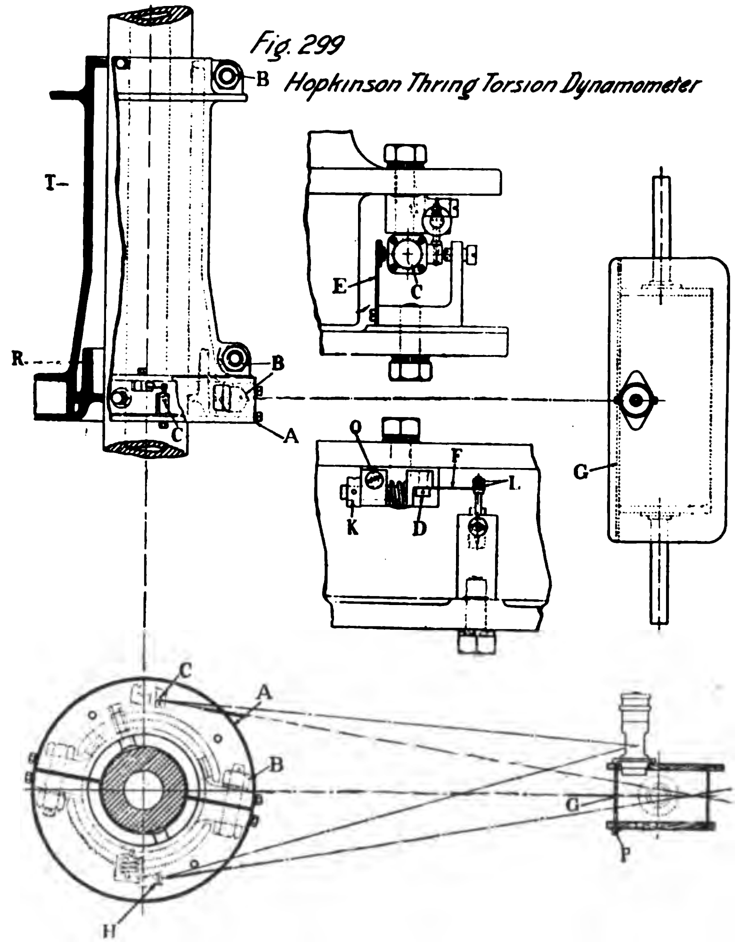
Another electrical type of torsion meter, due to the same investigators, depends upon the variation of the voltage in the secondary of a transformer with the magnetic reluctance due to different lengths of air-gap in the circuit. In this torsion meter two sleeves or tubes are fixed on the shaft, their ends being at a known distance apart, one sleeve is long and the other short. Where they abut they do not touch, but are furnished with projecting arms. When the shaft is transmitting power, and subjected to torsion, the two arms move relatively to one another, the displacement being proportional to the torsion of the shaft, the length of which extends between the circumferences embraced by the two sleeves. On one arm of a sleeve the primary coil and core of a small transformer is fixed and the secondary coil of the transformer is attached to the arm of the other sleeve, while a small air-gap separate the adjacent ends of the cores of the transformer. From this it will be seen that the air-gap length changes with the angle of torsion. The currents through the transformer are so led by means of slip-rings to brushes and return wires or earths that the primary may be excited by a small motor-driven alternator, while the secondary is connected to an alternate current voltmeter; so that the reading of the voltmeter is proportional to the angle of torsion and the voltmeter becomes the torque meter. The torque meter is calibrated in fractions of an inch of air-gap length and therefore of torsion; the scales are divided in tenths, hundredths, and thousandths of an inch, the smallest division being easily subdivisible by eye; the error of observation is said to be practically nil.

*Hopkinson-Thring Dynamometer.*—The principle of the apparatus designed by Professor Hopkinson and Mr. Thring is a differential one and consists in the observation of the twist between two adjacent points on the shaft by means of two beams of light projected on to a scale from a fixed and a movable mirror. The beam projected on the scale by the fixed mirror is taken as the zero point, whilst the beam projected by the movable mirror indicates the amount of torque on the shaft. Both mirrors rotate with the shaft, the reflections appear as continuous lines of light across the scale, even at moderate speeds.

The torsion meter is shown in Fig. 299, mounted on a shaft. A collar *R*, clamped to the shaft of which the torque has to be measured, is provided with a flange projecting at right angles to the shaft and an extension.

A sleeve *T* provided with a similar flange and extension at one end, is clamped at its further end on to the shaft in such a manner that its flange is close to that on the collar, whilst its extension overlaps that of the collar, on which it is supported to keep it concentric. Both the

collar and sleeve are quite rigid, and it is therefore obvious that when the shaft is twisted by the transmission of power, the flange on the sleeve will move relatively to that on the collar, the movement being equal to that between the two parts of the shaft on which these fittings are clamped. This movement is made visible by one or more systems of




torque mirrors mounted between the two flanges, which reflect a beam of light, projected from a lamp, on to a scale divided in a suitable manner on ground glass.

Each system of torque mirrors consists of a mounting, pivoted top and bottom on one or other of the flanges, in which two mirrors are arranged back to back. This mounting is provided with an arm, the end of which is connected by a flat spring to an adjustable stop on the other flange. Any relative movement of the two flanges will turn the torque

mirror and thereby cause the beam of light to move on the scale, the deflection produced being proportional to the torque applied to the shaft. Hence, if the rigidity of the material and the number of revolutions per minute are known, the horse-power transmitted can be calculated.

With the arrangement described, a reflection will be received from each mirror at every half-revolution of the shaft; but where the torque varies during a revolution (as with reciprocating engines), a second system of mirrors may be arranged at right angles to the first system, so that four readings can be taken during one revolution; or, if two scales are used, eight readings can be taken.

The beam of light is reflected by the mirror when in its highest position passes through the upper part of the scale; while the second reflection will occur when the mirror is in the position occupied by the zero mirror, the beam of light passing through the lower part of the scale. The position of the torque mirror is such that if the reflected beam strikes the scale to the right of the zero line, when the shaft has made a further half-revolution, the reflected beam from the other mirror will strike the scale to the left of the zero line. Obviously the deflection on both sides should be equal.

The fixed mirror is attached to the flange *T*. This must be adjusted so that the beam of light reflected from it is received at the same point on the scale as those from the movable mirrors when there is no torque on the shaft. To facilitate the erection and adjustment of the apparatus, the box containing the scale and carrying the lamp is fitted with trunnions, so that it can be inclined as required.

If the position of the apparatus becomes altered relatively to the scale owing to the warming up of the shaft or from other causes, this is indicated immediately to the observer by an alteration in the position of the zero as reflected by the mirror. Hence, the scale zero may be adjusted, if desired, by moving the scale so that its zero coincides with the reflection from the fixed mirror, but this is not necessary to obtain a correct result, since the mean of the two readings will be the same.

The constant of the instrument, viz. the factor which, when multiplied or divided into the product of the torsion-meter reading and the revolutions gives the horse-power, may be calculated within 2 or 3 per cent, if the section of shaft within the instrument is uniform.

But a direct calibration of the shaft with the instrument in position before the former is put into the ship is to be preferred. This is easily effected by applying a known twisting couple.

This torsion meter has been used in warships and other turbine-

driven steamers, running at speeds up to 1500 revolutions per minute. The smaller sizes of the instrument are designed to run up to 3000 revolutions per minute.

*Bevis Gibson.*—This apparatus (Fig. 300) employs two discs fixed at a distance apart on the shaft, each of the discs being provided with narrow radial slots. Behind the disc $A$ is fitted a lamp enclosed in a case, but having a slot in the side directly opposite to the slot in the disc. While behind the disc $B$ is fitted a measuring device consisting of an eye-piece with a micrometer traverse adjustment. The object glass has a slot similar to that in the disc.

When all the four slots are in line, a flash of light is seen in the eye-piece every revolution of the shaft, and for speeds above about 50 revolutions per minute the illumination appears almost continuous. When the shaft is transmitting power the discs are displaced relative to each

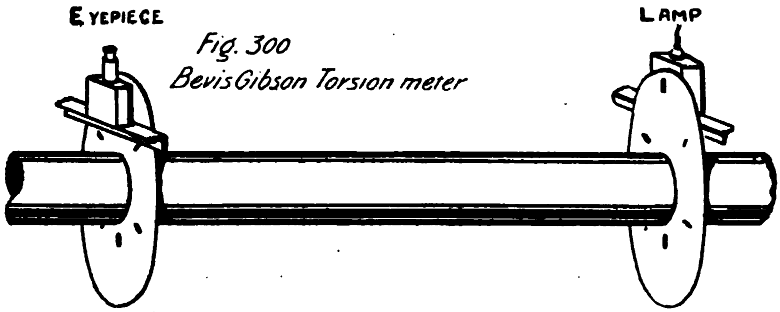


Fig. 300
Bevis Gibson Torsion meter

other and the slot in $B$ has passed beyond the eye-piece before the slot in $A$ has reached the position to allow the light to pass through. The eye-piece must therefore be displaced by an amount equal to the deflection of the shaft before the slots are again in alignment. To obtain the zero setting the shaft is rotated at approximately the normal speed without load and this reading is used as datum mark for subsequent measurements.

The slots in the disc have appreciable width, and to minimize errors due to this cause the setting of the eye-piece should always be made so that the light is just disappearing when traversing in one direction.

If the torque varies cyclically during each revolution, such as in the case of reciprocating engines, readings can be taken at several points in the revolutions by using a number of slots at the particular points desired in the revolution, but at different radial distances to avoid confusion. Then by moving the lamp and eye-piece radially to bring them into coincidence with the different slots it is possible to obtain a series of

values for the torsion. It is stated that the method is sensitive to angular difference of one hundredth of a degree.

*Amsler Torsion Meter.*—Dr. A. Amsler has devised a dynamometer very similar in principle to the above-described. This instrument has two slotted discs carried at the ends of a sleeve, one end of which is rigidly fixed to the shaft. Close to the disc on the free end of the sleeve is a third disc fixed to the shaft, and on this disc is engraved an angular scale over a short length of the circumference opposite the slots in the other disc.

This scale can be observed through the slots in the discs when the shaft is rotating, and if the speed is high enough the scale appears stationary.

The method in principle is a direct measurement of angular deflection and was used by Amsler in conjunction with a short length of very flexible steel shaft, this being used in order to obtain greater deflection with a compact form of instrument.

It should be observed that in all torsion meters used for shafts under axial load, such as the propeller shaft of a ship, an uncertain error may exist due to the combined load of torque and thrust.

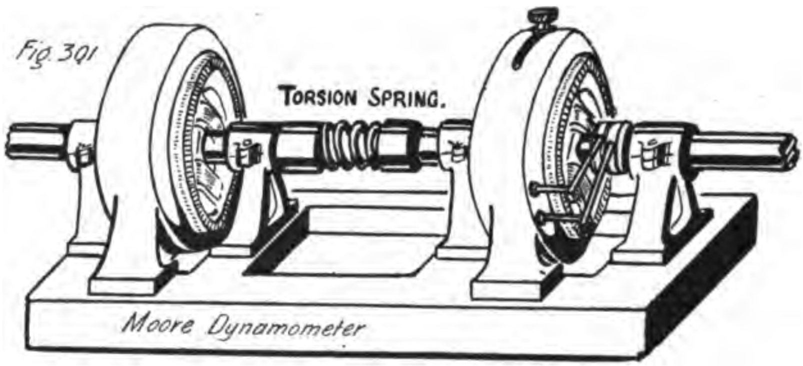
The magnitude of the effect of thrust does not appear to be accurately known, but according to some observers may cause an error of several per cent in the estimation of the power.

When torsion dynamometers are employed for the determination of small powers or in special investigations it is generally possible to make special provision for the measuring instrument, and in such circumstances the ease of operation is greatly facilitated by the use of a spring coupling as the deflecting member of the apparatus. Ayrton-Perry, Morin, Ruddick, Dalby, and numerous other investigators have devised dynamometers incorporating springs in this capacity. One example of this class of dynamometers due to Moore, presents some very novel features in the application of electrical measurements to the problem.

Mr. C. R. Moore succeeded in employing electrical means not only to measure the angle through which a spring connecting the two shafts of a transmission dynamometer is twisted, and hence the driving torque, but also automatically to multiply this by speed, so that the power being transmitted can be read at any moment upon a voltmeter.

Each shaft carries a small alternator with a two-pole field magnet (as shown in Fig. 301), and the exciting current, sent through the two in series, is necessarily the same for each. In all other respects the two machines are made identical, and they are so designed as to give very

accurately a simple harmonic wave form to the alternating electro-motive force which they induce. The two machines are so connected and adjusted that they are in exactly opposite phases when there is no torque and consequently no twist in the spring. When, however, one shaft is transmitting power to the other, the exact opposition of phase no longer obtains. In consequence of this the circuit, which consists of the two armatures in series and a voltmeter, is no longer dead, but an outstanding voltage is available to act on the voltmeter; and this voltage is proportional to the torque multiplied by the speed, so the readings of the voltmeter at once give the power being transmitted at any moment, and the two independent readings of speed and torque need not be made. Further, by the use of a switch, one of the connections can be reversed, then the voltmeter which indicates the vector sum of the two separate voltages or either voltage may be read so as to ascertain the speed.




It is well known that when two equal harmonically varying quantities having the same period are compounded, the resultant is a harmonically varying quantity of the same period and of an amplitude which is zero when the components are in exactly opposite phase, which is their arithmetical sum when they are in the same phase, and which, when there is a small departure from opposition, is almost proportional to the difference of phase at small angles.

The resultant varies as the sine of half the angle of phase difference, but since for angles up to 20 degrees the departure of the value of the sine from a straight line is only $\frac{1}{2}$ per cent, and it is less than $\frac{4}{5}$ per cent, at 25 degrees the resultant may be assumed proportional to the deflection. The quantity indicated by the voltmeter is proportional not only to the angle, but also to the absolute magnitude of the harmonic waves. As these are proportional to the speed the indication of the voltmeter is proportional to the torque multiplied by the speed or to the power being

transmitted. By the use of a switch one phase may be reversed, then the E.M.F. due to one alternator is shown on the voltmeter ; and this at once gives the speed. Provision is made for adjusting the phase of one of the alternators by the screw and slot shown on the right-hand machine so as to obtain exact opposition of phase, and this is adjusted so that the voltmeter reads zero when the dynamometer is running, so as to eliminate the small losses therein. It will of course be clear that the electrical load due to the alternators is very small, for the only output is that needed to actuate a voltmeter and overcome friction ; the load practically undiminished is transmitted through the dynamometer.

## III. Absorption Dynamometers

Dynamometers in which the entire output of the machine under test is dissipated as heat are known as absorption dynamometers. Such instruments may operate on the principle of (*a*) solid friction ; (*b*) eddy currents ; (*c*) electrical generation of current ; (*d*) fan brake, or (*e*) hydraulic friction.

The commonest form of brake used in engineering practice and the simplest to construct is the rope friction brake. This device was invented by Lord Kelvin in 1858, primarily for use in laying the Atlantic cable.

The brake consists of two or more hemp or cotton ropes passed around the pulley or fly-wheel of the motor ; the ropes being prevented from slipping off by the use of grooved wooden blocks fixed to the ropes at short intervals. The load is applied by hanging equal weights on the ends of the ropes and the torque applied is read on a spring balance. The power absorbed is readily calculated by multiplying the pull on the spring balance by the linear speed of the surface of the pulley.

Manilla ropes are generally run dry, but cotton ropes work better if lubricated by soaking in tallow and graphite. When rope brakes are employed for the measurement of more than a few horse-power, difficulty is usually experienced in dissipating the heat generated and the fly-wheels have to be water-cooled. For this purpose the fly-wheel is cast with trough-shaped section and the water fed into it, centrifugal force causing the water to remain as a layer around the inner circumference if the speed exceeds a certain minimum determined by the diameter of the wheel.

The most notable development which has been made in the design of the rope brake has been the method of making the brake automatically compensated for varying load. James Thomson varied the angle sub-

tended by the ropes on the wheel by the use of a loose pulley. Imray also employed a somewhat similar principle by the use of a sector-shaped lever.

The old cable brake of Appold and Amos has also been developed into a compensated type of brake. In this dynamometer a flexible band brake embraces the pulley and both ends of the band are coupled to a short toggle lever. A slot in the end of the lever engages with a fixed stud, so that a displacement of the band backwards or forwards increases or decreases the tension and so varies the friction.

The torque is measured by means of a weight hung from a point on the horizontal diameter. The friction is initially adjusted by a screw. The toggle lever is liable to introduce a certain force, and thus may introduce errors in the reading unless the lever is always adjusted so that it is in the same position when the observations are taken.

*Griffin's Friction Dynamometer.*—This instrument is also of the solid friction type, but is water cooled in a particularly effective manner.

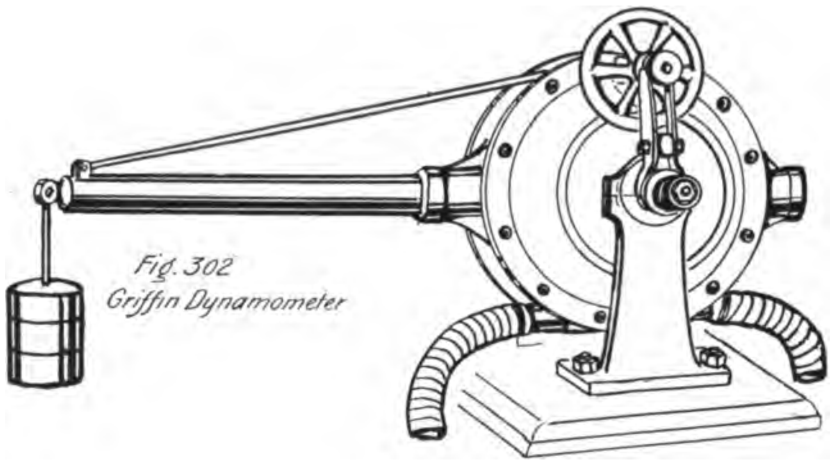


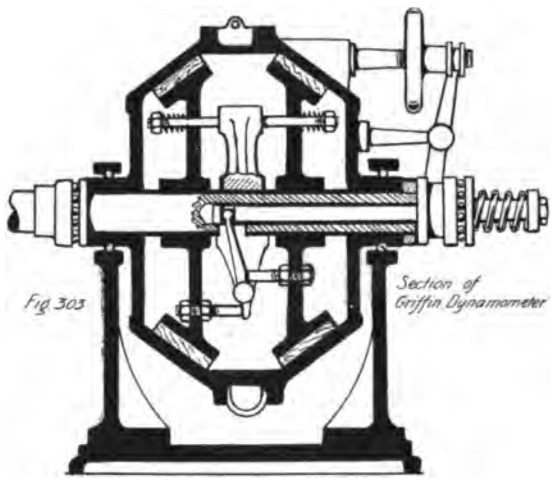
Fig. 302
Griffin Dynamometer

The general appearance of the device is shown in Fig. 302. The cast-iron case is turned inside in the form of two hollow cones, and lignum vitæ shoes may be pressed against these interior conical faces by means of a stationary hand-wheel through the intervention of mechanism shown in the illustration (Fig. 303).

The casing is mounted on ball-bearing to reduce friction, and water is passed through the interior of the casing for cooling purposes. The direction of rotation is such that the long arm, which is stayed, as shown, tends to lift the weight at its end, a spring balance being usually fitted in addition for convenience in working. The horse-power is of course determined by the speed of rotation, the length of the arm, and the

force at its end. A socket is provided on the opposite side of the casing to take the arm when it is desired to test the horse-power of a shaft running in the opposite direction. For ordinary use at high speeds the shoes are removed out of contact with the friction surfaces by means of the hand wheel, and "water attrition" alone is relied upon for taking up the load, in which case the characteristic relation between torque and speed follows approximately a square law, being due entirely to fluid friction. The makers recommend that water should be supplied at the rate of about five gallons per brake-horse-power hour. The inlet and outlet water pipes are shown at the bottom of the casing. The distance between the shoes and the casing or the pressure between them may be regulated by the hand wheel and the resistance adjusted while the load is on. This dynamometer has the advantage that the water supply may be taken from a tank very little above the dynamometer level, as no hydrostatic pressure is required to overcome internal pressures.

Fig 303



Section of Griffin Dynamometer

The indications of this dynamometer are very steady as compared with those of an ordinary friction brake. The same dynamometer is applicable for powers ranging from 5 horse-power at 250 revolutions per minute to 70 or 80 horse-power at 3000 revolutions per minute.

*The Alden Fluid Friction Dynamometer.*—This dynamometer, invented by Mr. G. I. Alden, depends for its action upon the friction between the lubricated surface of rotating and stationary discs and is very similar in action to a plate clutch. An unique feature is the method of applying the pressure hydraulically.

The construction and action of the brake is as follows :

The discs $D$ (Fig. 304) are fixed to the hub, which is keyed to the shaft and therefore revolve with it. On each side of these revolving discs are thin copper plates $C$, which form water-tight compartments with the outside stationary casing. These plates are forced towards the rotating discs by the pressure of water in the spaces $W$. The rubbing surfaces of the discs $D$ and the copper plates $C$ are lubricated with oil,

which is fed into the hub and is carried outwards to the circumference by centrifugal action, where it escapes and is returned to the hub by external pipes. An oil reservoir connected to each pipe provides for leakage. The bearing surface between the hub and casing is lubricated by the oil which leaks past the packing rings. This oil is caught by drip-cups.

Water under pressure circulates through the spaces $W$, and presses the copper plates towards the revolving discs, the resistance to rotation being due to the viscosity of the lubricating oil. The water also carries away the heat which is generated by the frictional work.

The moment on the brake can be measured and the brake-horse-power calculated in the usual manner. An advantage of the brake is the ease

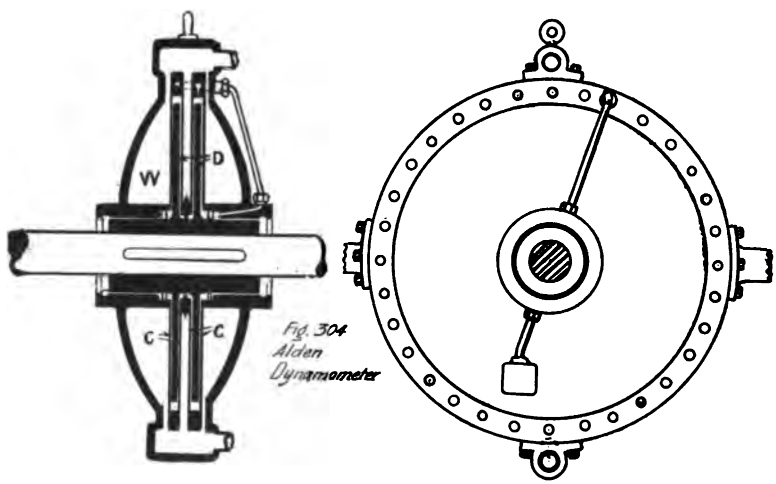



Fig. 304
Alden
Dynamometer

and rapidity of control, since the water pressure can be varied almost instantly and the adjustment can, of course, be performed from a distance. The control of the water pressure is sometimes arranged automatically by the movement of the casing.

It is stated that the maximum rubbing speed of the discs should not exceed 7000 feet per minute, and for the best condition the surface should be between 6 and 10 sq. in. per horse-power.

The Alden type of brake has recently been used for testing high-power water-turbines up to about 3000 b.h.p. when running at 225 revolutions per minute. In this case a series of discs and diaphragms were built up in connection with a single external casing.

*Eddy Current Dynamometer.*—The effect of rotating a magnet near a conducting disc has already been referred to in Chapter VI when dealing with the magnetic speedometer and also in the discussion on methods of damping.

The phenomenon of magnetic drag when used in conjunction with a magnetic field of variable strength, such as an electromagnet, constitutes a very convenient means of adjusting the brake load on a machine, and the reaction between the parts affords an accurate method of measuring the torque. Several designs of eddy current dynamometers have been introduced from time to time, especially on the Continent. Dr. Morris and Mr. Lister carried out a thorough investigation of the action of this class of instrument in the case of a fourteen horse-power brake they designed and constructed for the Birmingham University. (See Fig. 305.)

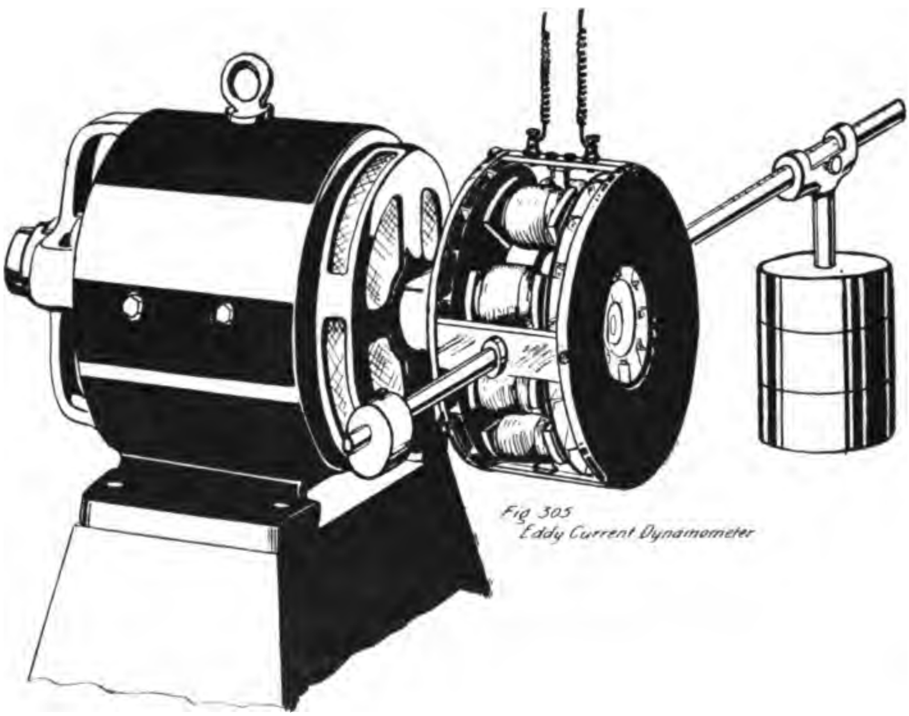


Fig 305
Eddy Current Dynamometer

This brake, shown in detail in Fig. 306, consists of two copper discs, each mounted on a cast aluminum spider $C$. These are made fast, one at either end of a sleeve $A$ which is keyed to the shaft of the motor under test. Riding loose on this sleeve and between the two copper discs is an aluminum casting $F$ carrying a number of electromagnets, wound so as to have alternate polarity. These magnets consist of well-ventilated coils $L$ on circular cores $K$ fitted with pole pieces $H$. To the outside of each copper disc is secured a ring of wrought iron $D$, which revolves with the copper and at the same time forms a path for the magnetic flux. These iron rings are fitted with cooling vanes $E$. When the motor is running the magnetic flux in traversing the moving copper induces eddy

currents. All this absorbed energy in the copper discs is converted into heat and dissipated by the cooling vanes. At the same time the flux tends to drag round the magnet system and lever $P$. By suitably adjusting the exciting current the lever floats. The power is then found in the usual way by multiplying the torque by the number of revolutions per minute. When in equilibrium the lever floats between stops, in an horizontal position. The bar carrying the weights is rigidly fixed at right angles to the arm, so that when the lever drops below the horizontal position the effective radial distance of the weight is reduced, and if the lever is above the horizontal the effective radius is increased, but when the lever is horizontal the weight acts at a definite measured length of

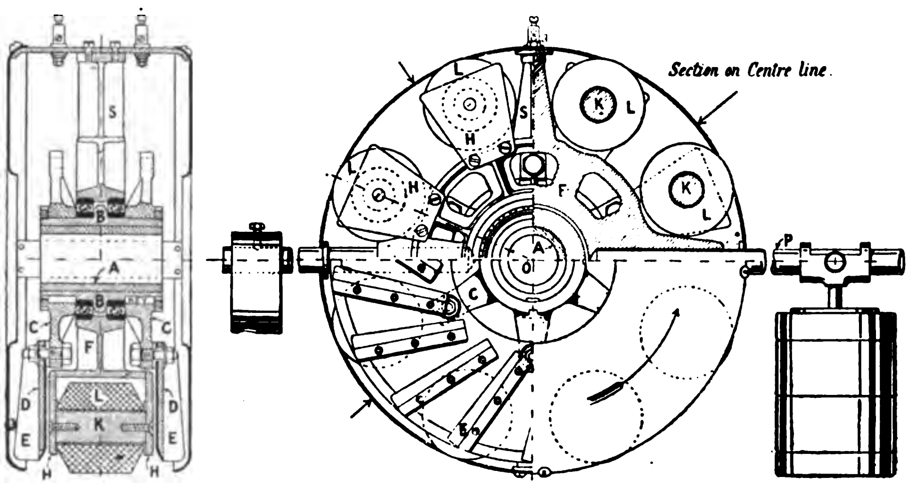



Fig 306 · Eddy Current Dynamometer

lever to which it is adjusted. The characteristic curve of the relation between torque and speed is shown in Fig. 307. This curve is plotted for a thick-rimmed disc referred to later and a flux density of 4000 amp. turns per coil. The torque falls off above a certain speed for all flux densities.

Morris and Lister developed a theory for the action of brake and their conclusions are of considerable interest in their bearing on the design of this class of brake. General considerations indicate that the eddy current disc should be I-shaped with thick rims in preference to a plain disc. The thickness $t$ of the web or portion cutting the magnetic flux is given by the term

$$t = \frac{a\rho}{2\pi v} \tan \theta.$$

where $a$ is a resistance factor depending upon the ratio of the resistance of the eddy current path in the web to the resistance of the path along the rims. It is stated that this factor should be approximately 1·5.

$\rho$ = specific resistance of material of disc in C.G.S. units at the working temperature.

$v$ = speed of disc at pole centre line in cms./sec.

$\tan\theta$ = angle of flux inclination to pole surface due to rotation of disc (varying directly as the speed).

The best value of $\tan\theta$ at a given speed is shown to be $\frac{1}{\sqrt{3}}$, so that the thickness of the disc in millimetres may be stated to be equal to the specific resistance of its material when heated (about 2500 for copper and 4000 for aluminium) divided by the average linear velocity of disc in centimetres. Any greater thickness than the above will result in a decrease of torque. The calculated torque curve agrees well with the curve already given in Fig. 307. The authors also deduced a general expression for the horse-power absorbed by a brake of given dimensions, using the most advantageous thickness given above.

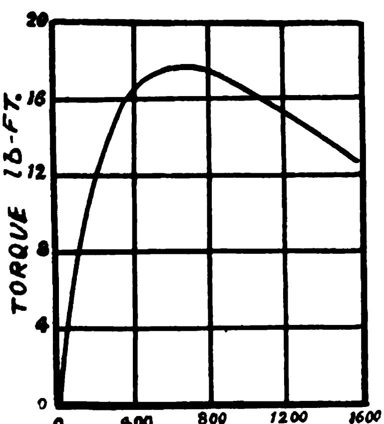


Fig. 307

Thus approximate maximum :

$$B.H.P. = 3\times 10^{13} - B^2D^2RZ.$$

$B$ = main flux due to poles (lines per sq. cm.).

$D$ = diameter of disc at pole centres in cms.

$R$ = speed of disc R.P.M.

$Z$ = radial length of average eddy current path or width of web between rims.

This expression assumes a value of the ratio of pole-face width to pole pitch of 0·6 to 1 and a leakage of 25 per cent of the flux.

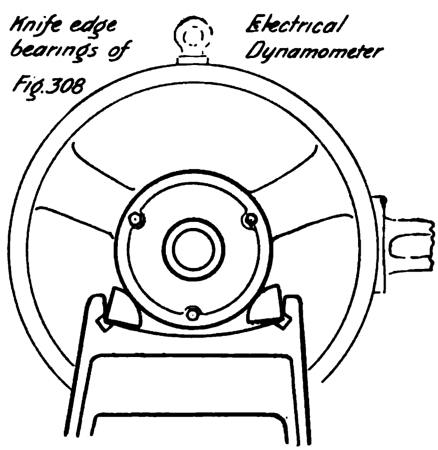
It is interesting to note that the eddy current principle is utilised in very large powers as a brake on electric winding plants, several of which are in use in South Africa. These particular examples consist of rotating field-magnet systems exactly similar to low-speed alternators, fixed on the winder drum shaft, and revolving within a hollow cast iron stator ring, with a smooth circular face opposite to the field-magnet poles. Eddy currents are set up in the face of the ring when the magnet system

is excited, which exert a very considerable and effective braking force without jerk or jar of any kind. Water is circulated through the hollow casting of the stator ring to carry off the heat which is generated. Brakes of this type are capable of absorbing over 2000 horse-power with an expenditure of energy in the field-magnets at the rate of 45 kilowatts, i.e. about 3 per cent of the power absorbed. This excitation current is supplied by motor generator with field control to avoid opening the circuit of the field-magnets, the self-induction of which would cause heavy sparking.

Hence if the necessity arose it is evident that an eddy current dynamometer could be built for dealing with very large powers.

*Electrical Generator Dynamometers.*—Approximate estimates of output are often effected by connecting the prime mover under test to a dynamo; the various losses of the dynamo being determined by separate experiments with no load. The method is fairly satisfactory for large powers, particularly if two similar dynamos are available on which an Hopkinson efficiency test can be carried out. For small powers, however, the constancy of the various losses is not to be relied upon, so the results cannot lay claim to high accuracy.

It is, therefore, preferable to directly measure the reaction on the casing of the dynamo. This measurement is sometimes effected by mounting the casing on ball bearing journals, but the friction is not negligible. Dr. Drysdale states that in one particular instance, with a 10 h.p. dynamometer the error due to journal friction amounted to as much as 5 per cent. Consequently he modified his machine to permit of it being suspended from a balance beam swinging on knife edges. This expedient introduces difficulties with the coupling of the dynamometer, and for heavy machines friction wheels would probably be simpler to use.




Drs. Stanton and Bairstow at the National Physical Laboratory have devised a very convenient system of mounting the dynamo casing. In this the two end covers are furnished with turned projections concentric with the shaft. Each of these cylindrical extensions of the dynamo casing rests on two knife-edges bearing on vees let into the supporting frame, as shown in Fig. 308, the knife-edges from sectors of circles whose axis is at the sharp edge, and thus the

casing in effect rests on friction wheels having a minimum of frictional resistance to rotation.

The complete dynamometer is shown in Fig. 309 and has given excellent results in practice, the knife-edges show no tendency to slip downwards even with very unsteady loads.

Electrical dynamometers can, of course, be made regenerate by employing the current generated for heating, etc., and one large engine-testing plant utilised the electrical energy to prepare electrolytic hydrogen for airships' filling.

Dynamometers of the electric type have one minor disadvantage when

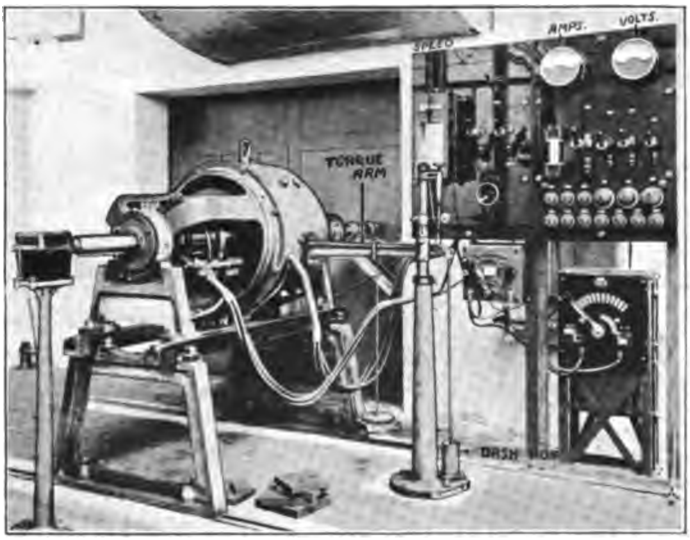



*Fig. 309.*

used for testing internal-combustion engines—the inertia of the rotating armature is considerable and does not permit of the engine being pulled up quickly in the event of an accident.

*Hydraulic Dynamometers.*—The best known and most extensively used dynamometer of this class is that of Froude. This instrument was devised by Mr. William Froude in 1876. It depends for its action on work done by a rotor in discharging water at high speed from its periphery into cavities formed in the casing. The rotor and the casing together form elliptical receptacles in which the water courses around at high velocity. The resistance offered by the water to the motion of the rotor reacts on the casing, which tends to turn on its supports. The moment of this force is balanced by means of a weighted lever in the usual manner.

A typical medium power brake is shown in Fig. 310, a section of which

is given in Fig. 311. The rotor spindle runs on ball-bearings in the casing and the casing itself is carried on ball-bearings in a fixed frame. In larger sizes the ball-bearings are replaced by friction wheels. The

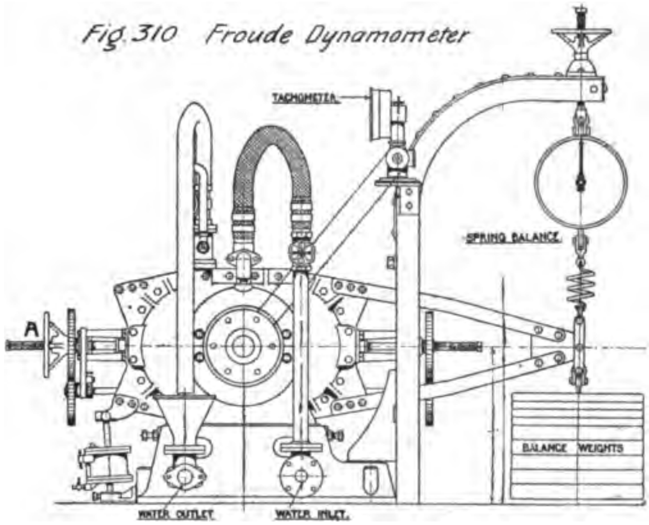


Fig. 310 Froude Dynamometer

diagram at the right-hand corner of Fig. 311 is a section through the rotor and casing showing the form of the vanes.

In order to vary the power absorbed by the brake the rotor can be blanked off from the casing by means of sluice plates which project in from both sides. These plates can be adjusted from the exterior of the

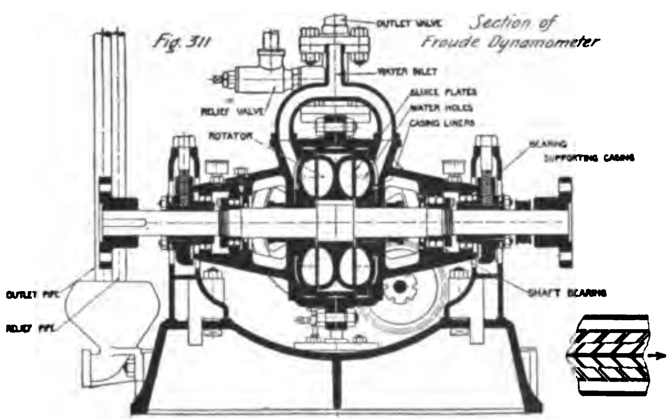


Fig. 311 Section of Froude Dynamometer

brake, whilst running, by means of a hand-wheel and screw shown at $A$ in Fig. 310. The circulating water is supplied to the brake under a pressure of 10 to 30 lb. per sq. in. and a minimum amount of two gallons per brake-horse-power per hour is recommended.

Froude dynamometers have been constructed for dealing with very

large powers, and an illustration of a 5000 b.h.p. machine made by Messrs. Heenan and Froude for testing internal-combustion engines at about 200 r.p.m. is given in Fig. 312. This type has a cast steel rotor, but is not fitted with sluice plates, the regulation being effected by a valve on the water supply. There is in addition an automatic control on the water supply by levers interconnected to the weighing arm to maintain a constant torque.

In the standard type of Froude dynamometer the reaction varies as the square of the speed of rotation of the turbine, since the momentum

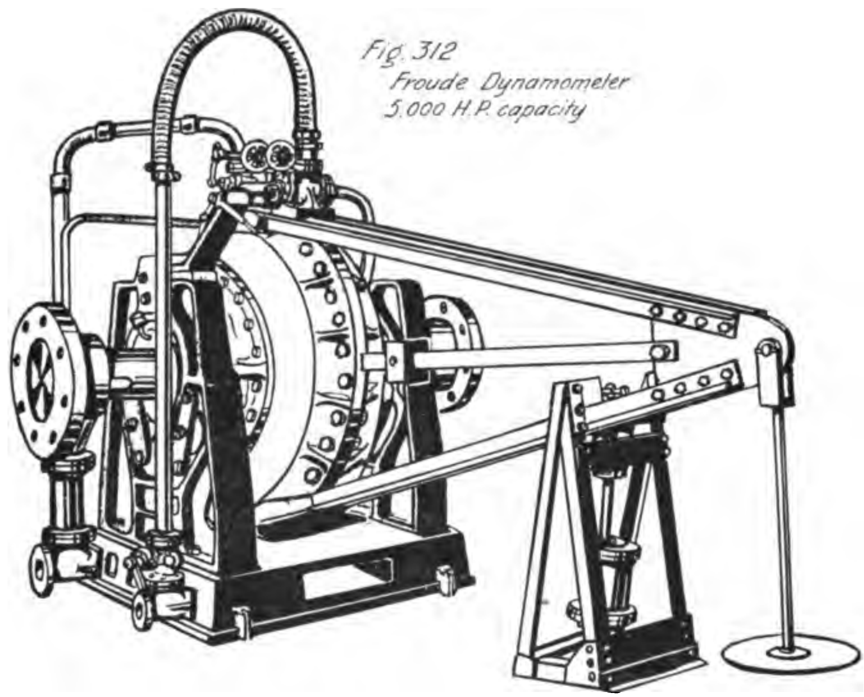


Fig. 312
Froude Dynamometer
5,000 H.P. capacity

generated per second, causing the reaction, varies as the product of the mass operated on per second and the speed imparted to it ; the speed is that of the turbine, and the mass operated on varies as the speed of "vertical rotation," which is as the speed of the turbine.

Froude deduced from the general considerations indicated below that for two similar dynamometers of different dimensions that for the same speed of rotation their respective moments of reaction should be as the fifth powers of their respective dimensions.

Let two dynamometers, $A$ and $B$, be compared, the diameter of $A$ being double that of $B$, the revolutions per minute of both the same, the linear velocity in $A$ would be double that of $B$, and from this cause

the resistance would be as the square. In $A$ the area acted on would be four times as great as that of $B$, or as the square of the increase in dimensions; thus we should have four times the resistance acting on four times the area in $A$, and therefore the effective resistance is proportional to the fourth power of the increase of dimensions. Also the resistance would be opposed at the end of an arm of double the radius; so that finally the power-absorbing capacity of the dynamometer would be proportional to the fifth power of its linear dimensions.

Experiment showed that this deduction was approximately true. Two similar water dynamometers were made, in which the diameters of the turbines were 12 and 9·1 in. Now $\left(\frac{12}{9 \cdot 1}\right)^5 = 4$, so that at a given speed of rotation of the turbines the ratio of the moments of the two machines should be 4. The ratio turned out to be 3·86. The small difference is attributed to the fact that in the larger of the machines the internal friction was rather less in proportion than that in the smaller one.

*Fan Dynamometers.*—In this class of dynamometer the power of the rotor is dissipated in churning the air with a rotating fan. The device is usually constructed with two or more arms carrying flat plates at adjustable distances along their lengths. A two-blade fan is shown in Fig. 313. The power absorbed is varied by changing the position of the plates, and this, of course, necessitates stopping down for each adjustment.

As will be shown later the power may be calculated from the dimension of the fan multiplied by the cube of the speed, but the more usual

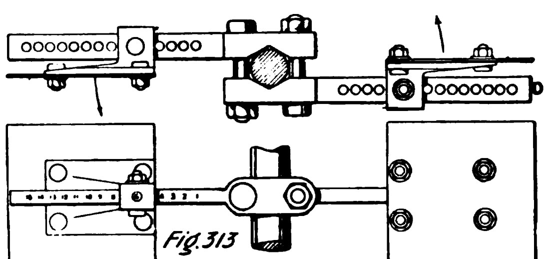


Fig. 313

Fan Dynamometer

procedure is to tabulate a series of coefficients for the various positions of the plates and multiply the appropriate factor by the cube of the speed.

Dynamometers of this type are very useful for "running in" aero engines, etc., where the engine has to be run at approximately full load for several hours. On account of the fact that this form of brake has a very steep characteristic the engine will run at a fairly uniform speed without attention.

In theoretical considerations of the fan dynamometers it is generally assumed that the resisting torque varies as :

(1) The fifth power of the linear dimensions (i.e. as the area of the fan blades and the cube of the radii of similar points).
(2) The square of the revolutions per minute.
(3) The density of the fluid in which the fan rotates.

From (2) it follows that the horse-power of a fan brake varies as the cube of the revolutions. Within wide limits this is found to be correct, but at very high speeds this law is not exactly obeyed and the torque varies as a power slightly less than the square of the r.p.m. The first fundamental assumption also is not strictly correct in practice, the torque is found to vary with a power between the fourth and fifth of the linear dimensions. This is due, of course, to disturbing factors not taken into account in the theory, such as the thickening-up of the arms which affects the stream line flow and also the feed of the air into the fan, the air flowing in at the centre and being driven out centrifugally. The horse-power varies directly as the barometric pressure and inversely as the absolute temperature.

Messrs. Morgan and Wood recently made an investigation of the fan dynamometer and their experimental results confirm those of Colonel Renard, that the resistance varies as the square of the speed of rotation.

An important source of error studied by these investigators was the influence of the confining walls of the building on the fan. The experiments were conducted with a number of rings built up near to and parallel to the plane of rotation on one side of the fan. The proximity of this surface reduced the power absorbed at a given speed by amounts as great as 20 per cent. If the fan was completed, boxed in with only an opening at the top, the power absorbed was reduced to such an extent that the apparent results were 194 per cent greater than the correct amounts. Hence it is essential that the fan should not be run near any obstruction unless calibrated under precisely the same conditions.

It might be mentioned that the method of experiment employed by Messrs. Morgan and Wood was to measure the counter torque of the engine by a cradle dynamometer arranged as follows :

A hollow bracket was mounted on a stationary frame carried with the inner race of a large ball-bearing, an extension of the crankshaft, concentric with the ball race, passing through but not touching the bracket. The outer ball race fitted in a housing which supports a transverse member which in the case of the fly-wheel end also formed the arm

from which the weights were suspended. The petrol tank was mounted with the engine and care was taken that the water connections caused no constraint. It was found essential that the exhaust should discharge parallel to the axis of the engine and that the pipe should be in no way constrained but should project some distance into a larger pipe. By the addition of counter-weights bolted to the " live " frame it was possible to bring the centre of gravity of the engine and frame in line with, but very slightly below, the axis of the supporting bearings.

Mr. J. L. Hodgson has carried out an interesting series of experiments with a fan dynamometer working in water. The object of the experiments was to determine the coefficient $K$ in the formula

$$T = K\ N^2\ r^5\ s\ {}^2W.$$

Where $T$ is the torque,

$N$ the number of revolutions per minute,

$s$ the length of the side of a square blade or diameter of a round blade in inches,

$r$ the external radius of the fan,

$W$ density of fluid in which fan rotates in lb. per cubic foot,

$K$ a coefficient which he concluded depended upon the value of $r/s$.

The results are of theoretical interest insomuch that they show the variation of the coefficient $K$ with the value $r/s$. It is, of course, obvious that the factors $r/s$ define the geometrical form of the fan regardless of its actual dimensions.

One would expect the coefficient to be dependent on this ratio since the blades cause a swirl of the air in their vicinity, and it would be anticipated that the influence of this swirl would be most pronounced for the smallest values of $r/s$.

Since when blades are nearest to the axis of rotation and the tendency would be for a mass of air to be carried round around with them. Such an effect is apparent in Hodgson's results, as will be seen from an inspection of Fig. 314.

The blades used were $\frac{1}{2}$, 1, and 2 in. square ; and $\frac{1}{2}$, 1, and 2 in. in diameter. These were cut from smooth German-silver sheet 0·012 in. thick, and the edges were left sharp and square. The fan spindle was driven by a small air turbine attached directly to it, and the driving torque measured by means of a manometer which indicated the pressure at the turbine jet. The relation between the driving torque and the readings of the manometer were determined by a series of brake tests

taken at various jet pressures and turbine speeds. The fan was rotated in a covered tank of still water 20 ft. square by 5 ft. deep, and the plane of the fan arms was 10 in. below the surface of the water. The coefficient of resistance was found to be constant for the largest diameter of fan used for all depths of immersion greater than 6 in.

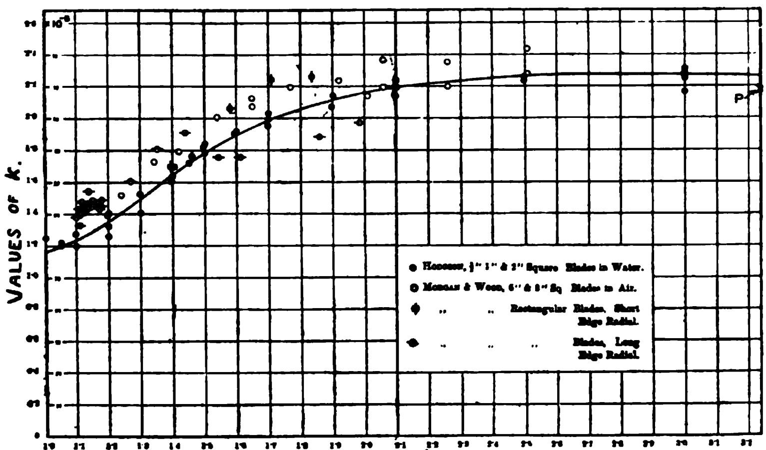



Fig. 314

Hodgson found that the torque of the arms which he employed could be represented by the equation

$$Ta = 0{\cdot}35 \times 10^{-8}\ \sigma N^2 r_a{}^4 t W.$$

Where $\sigma$ is a coefficient depending on the section of the arms varying 1·63 for a square section down to 0·15 for a stream form of the same thickness, but six times the length,

$r_a$ = radius of the arm in inches measured to the inside of the blades,

$t$ = thickness of arms in inches.

It was desirable to separate the resistance of the blades from that of the arm, and experiment has shown that if the width of the arms is small,[1] the resistance of the whole fan can without appreciable error be taken as the sum of the resistances of the arms and blades each calculated separately.

If $Tb$ is the torque due to the blades alone in inch lb.,
$Ta$ torque due to arms alone,
$T$ the total torque,

Then $T = Ta + Tb$

and $H.P. = \dfrac{TN}{63{,}000}$

[1] The width of the arms must be less than one-seventh that of the blades.

$W$ is the density of the fluid in which the fan rotates in lb. per cubic foot $=62{\cdot}33$ for water at 50° F.

$$=\frac{1{\cdot}317\times\text{barometric pressure in inches of mercury}}{(460+\text{Temp. in °F. for air})}$$

From an inspection of Fig. 314 it will be observed that Morgan and Wood's results[1] appear to be 2 or 3 per cent higher than Hodgson's. Whether this difference is a real thing or not cannot be decided, as it is almost within the limits of experimental error.

Hodgson's comparative results for square and round plates are of interest as they prove that the two curves are very similar. The range of $r/s$ covered is very much greater than in the case of the full scale experiment of Morgan and Wood.

The check-point $A$ was obtained with the fan rotating in air. It will be observed that it falls on a part of the curve where the coefficient has attained a really constant value. It is obvious that in practice it is advisable to avoid using such dimensions for the fan that the value of $r/s$ is less than 3.

The above experiments with a small fan rotating in water can be strictly comparable with those of a large fan in air from the point of view of the theory of Dynamical Similarity, since the conditions may be such that the product of the dimensions and the linear velocity of the plates divided by the kinematical viscosity was equal in the two experiments. This condition would imply that the product $N.r.s.$ for air equals $N_1 r_1 s_1/13$ for the case in water. Hodgson employed less than one-thousandth of an horse-power as compared with about 20 h.p. by Morgan and Wood. While it is very convenient to be able to calculate the coefficient of a fan dynamometer from a knowledge of its dimensions it must be remembered that the results obtained can only be regarded as approximate, and actual calibration on powers of nearly the same value as those which may be used in practice is essential for accuracy.

## IV. Worm Gear Dynamometer

The worm gear dynamometer devised by Mr. F. W. Lanchester is a distinct advance in the design of appliances for testing the efficiency of the elements of a machine. This dynamometer was developed primarily with the object of testing the performance of a new type of saddle-worm designed by Mr. Lanchester, but it has also proved to be of great service in the study of the relative lubricating efficiency of

[1] In reducing Morgan and Wood's results for a rectangular plate, Hodgson assumed a square plate of equivalent area in plotting on the above curve.

different oils under the very high pressures which obtain in modern worm gears. This, of course, can be effected by making efficiency tests of a worm with different samples of oil.

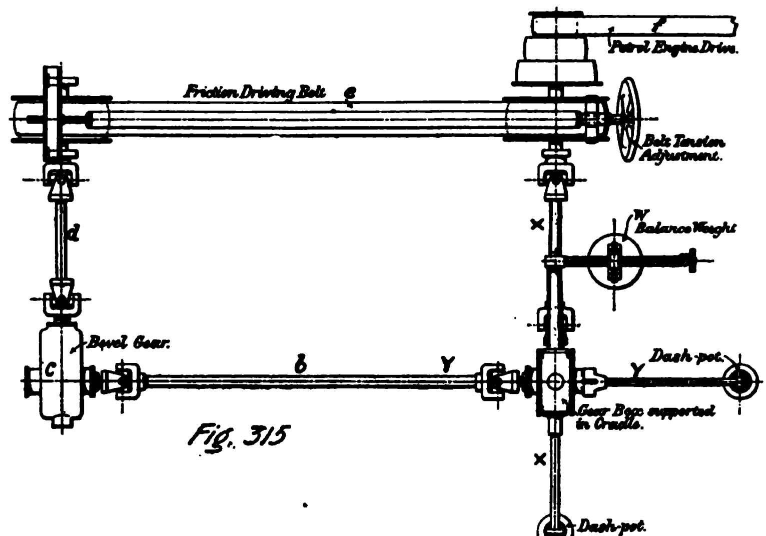
*The Testing of Worm Gear.*—The most important direction in which it is desirable to test worm gear is to determine its efficiency under various conditions of load and speed. Where the efficiency of any piece of mechanism is high, such tests, to be of any real service, must be carried out with a very great degree of accuracy. Thus, where an efficiency of 97 per cent, or thereabouts (as in a well-designed worm transmission), is obtained, it is useless to employ methods having an error of 1 per cent more or less. Any such error may be legitimately looked upon as a 33 per cent error in the measurement of the power wasted in transmission. If the tests are to give anything of a nature useful to the designer, improvement of his methods of generating, or to enlighten him as to the best conditions under which worm gear is to be employed, he must be able to detect with certainty variations in the amount of power lost of a far less magnitude than this. It might, in fact, be said that unless the loss of power can be determined to within about 5 per cent, the method of test must be looked upon as unsatisfactory. Thus, taking 96 per cent as a good average worm gear efficiency, the loss of power is 4 per cent, and the determination should be within an error of one-fifth of 1 per cent, and this degree of accuracy is obtained by the Daimler-Lanchester testing machine.

The dynamometer itself is described later. In principle the machine is an instrument for the direct comparative measurement of two torques acting about axes at right angles, or, more generally, about axes making any angle with each other. It is evident that in any gear transmission where there is no slip the efficiency is given by the ratio of the torques of the driving and driven elements divided by the gear ratio (or multiplied by the gear ratio if it is expressed in the inverse form). Thus if the efficiency were perfect the torque ratio and gear ratio would be identical.

In the Lanchester worm-testing machine the gear-box is supported in a cradle on ball-bearings, which are equivalent to a gimbal arrangement with practically frictionless joints. Further, by the introduction of universal joints in the driving and driven shafts, as indicated in the diagrammatic sketch of the machine shown in Fig. 315, no constraint is imposed by these shafts on small oscillations of the gear-box about its mean position, and, therefore, the externally-applied torque required to balance the gear box when running in the position in which its axes are parallel to the axes of the shafts is equal to the resultant torque of

the two shafts, and the ratio of its components about these axes will be the ratio of the torques on the shafts.

For any given conditions of running it is found that there is a neutral axis about which the torque is zero ; this is at right angles to the plane of the resultant torque, and is determined by the adjustment of a sliding jockey knife-edge. This knife-edge and the centre of the double gimbal mounting define the line of zero torque, and when the floating system is in equilibrium the position of the knife-edge gives the torque reading required. At every reading the machine is brought to its zero position about both co-ordinate axes ; it is steadied by appropriately arranged




THE DAIMLER-LANCHESTER WORM GEAR TESTING MACHINE

dash-pots. The power transmitted by the gear is restored to the driving shaft through the medium of a bevel gear and slipping belt.

The total torque transmitted is in every case measured immediately before the torque ratio is read and gives the measure of the total power transmitted ; any error that may creep in between the times of reading the transmission torque to determine the horse-power and reading the torque ratio to determine efficiency owing to changes in the external conditions, such as the slip factor of the belt, is of no importance, owing to the fact that the changes of efficiency for such small changes of load or speed as are liable to occur are quite negligible.

A section of the cradle is shown in Fig. 316. The worm-box is mounted on ball-bearings so as to have freedom of motion about the axis of the driving shaft $XX$ and the driven shaft $YY$. The driving and driven

shafts are connected to the worm shaft and wheel shaft in the box by means of universal joints so arranged that any turning moment about either axis is eliminated when the box is in the balanced condition. An arm is attached to the box in the direction of the $XX$ axis, but the balance weight is not attached to this directly, but to a bar fixed at right angles to the arm in a direction parallel to the $YY$ axis, and 24 in. therefrom. The balance weight is adjustable along this bar. The box is first balanced in both directions without the balance weight, and the torque in the driven shaft obtained by noting the balance weight lifted at the 24-in. radius. The torque on the driven arm is then balanced by sliding the weight along the bar until the box is balanced about the axis $XX$. If $W$ is the balance weight and $S$ the distance along the bar from

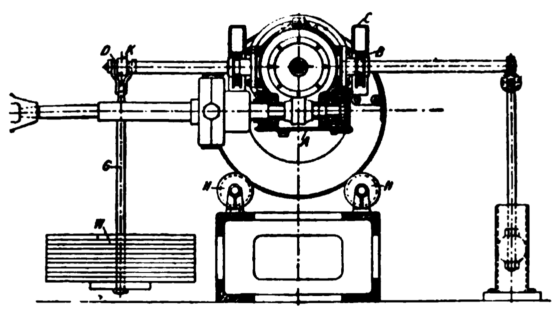


*Fig. 316 Section of worm gear testing cradle.*

*A* Worm-gear case.
*B* Ball bearings, carrying case allowing movement in cradle.
*C* Cradle, consisting of two circular discs coupled by bridges.
*D* Cross knife-edge.
*E* Adjusting wheel.
*F* Dial.
*G* Rod carrying weight.
*H* Anti-friction rollers.
*K* Balance arm, with knife-edge on upper face.
*W* Weights.

the arm, $W \times 24$ = torque of driven shaft, $W \times S$ = torque of driving shaft, and if there were no friction $W \times S / W \times 24 = r$, the gear ratio. To overcome the friction $WS$ has to be increased to $WS^1$ and $S/S^1$ will then be the efficiency $e$, or $e = 24 \times \frac{r}{S^1}$. It must be noted that the shift of the point of application of the load is not large. For example, if $r = \frac{1}{4}$, $S = 6$ in., and with 90 per cent efficiency, $S^1 = 6{\cdot}67$ in., so that 0·67 in. corresponds to a change in efficiency of 10 per cent. The efficiency measured during tests usually varies from 93 to 97 per cent, and for the gear given above $S^1$ would vary from 6·452 in. to 6·186 in. In actual work a variation of 0·01 in. from the mean position would make the box turn in one direction or the other about the axis $XX$, and consequently the determinations of efficiency are probably correct to 0·2 per cent, which is sufficient for practical purposes.

Referring again to the diagram (Fig. 315), it will be seen that the drive is taken by means of a shaft *b* to a bevel-box *c* with the large wheel driving the pinion, and that the shaft *d* carries a pulley from which a belt *e* is taken to a pulley on the driving shaft. This tends to drive the driving shaft at a slightly higher speed than the driving belt *f*, and by altering the tension in the belt *e* the pressure between the worm and wheel, and therefore the torque, can be adjusted to any desired value.

In this machine an absorption dynamometer is unnecessary since the gear is placed in the power circuit and the driving motor is only required to supply the loss of power which takes place in friction.

The method of doing this in the Lanchester gear is by so arranging the diameters of the pulleys connected by the belt *e* that the velocity ratio of the belt-drive is about 5 per cent greater than that of the gears. In this way the friction due to the slip of the belt over the pulley on the driving shaft supplies the greater part of the driving torque of the gear under test.

The apparatus is driven by a four-cylinder petrol motor, the speed of which can be varied to give a range of from 400 to 1500 revolutions per minute of the driving shaft. The speed is obtained by a tachometer driven from the driving shaft. The temperature is observed by means of a thermometer fixed in the top of the casing close to the top of the worm-wheel and placed in such a position that the oil is thrown off the wheel on to the bulb.

Many facts of practical importance both to the designer and the user have already been elucidated by the new dynamometer. One important result is the marked difference in behaviour that is found to exist between the various designs of worm gear.

From tests with various tooth pressures it appears that the oil film begins to break down in the case of the parallel worm at loads that the saddle form sustains without loss of efficiency. A second fact brought out of tests is that the loss of efficiency at reduced speeds is far less than previously supposed ; at the lowest useful motor-car speeds it rarely falls much below 94 per cent and it is quite exceptional to record efficiencies below 93 per cent.

A third fact brought out is the great variation in efficiency due to differences in the lubricants employed. An extensive series of experiments by Mr. Hyde have shown that in general mineral oils are inferior to animal or vegetable oils, and confirmed Mr. Lanchester's prediction that the viscosity of the oil is little or no guide in the selection of a gear lubricant.

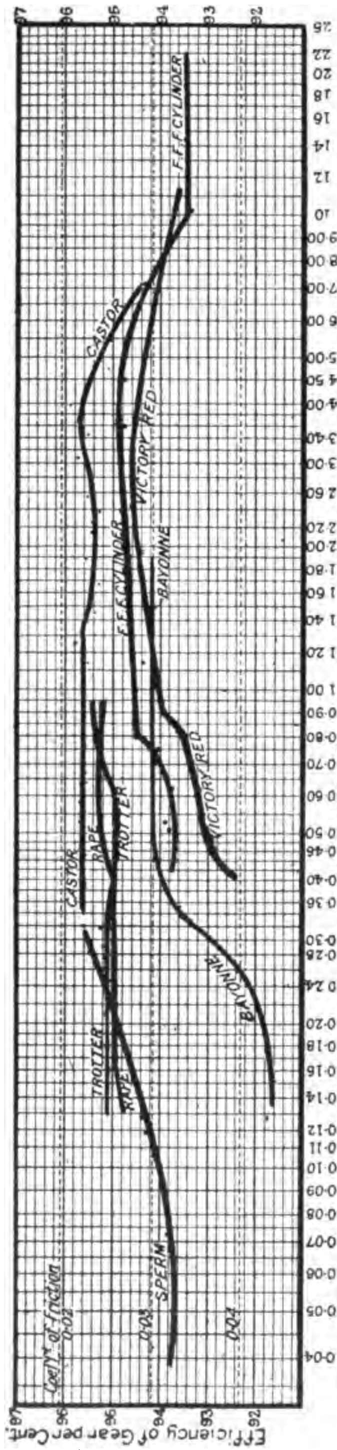



Fig. 317

VARIATION OF EFFICIENCY OF WORM GEAR WITH VISCOSITY OF OIL.

Mean Distributed Load on Teeth of Gear = $1\frac{1}{4}$ tons/sq. inch.

Mean Speed of Worm Shaft ... = 1080 revs./min.

Average Horse-Power Transmitted ... = $33\frac{1}{2}$.

It is well known, of course, that the viscosity of liquids such as ether and alcohol is increased enormously as the pressure is raised, and consequently it might be supposed that under the pressure prevailing between the worm and wheel in the gear that the viscosity of the lubricant might have a value very different from that obtaining at atmospheric pressure. Experiments on the viscosity of oils at very high pressure were carried out by Dr. Stanton and Mr. Hyde to test this point. Their experiments clearly showed that the viscosity of oils at high pressures was greatly increased, but the mineral oils showed a greater rise of viscosity with pressure than did animal and vegetable oils, and yet they are worse lubricants. Hence viscosity is not a sufficient criterion for determining the lubricating properties of an oil. The results of these experiments are shown graphically in Fig. 317.

The experiments with the Lanchester machine shows that the efficiency falls off with increasing temperature of the oil, but the variation is much less than would be anticipated from the change in viscosity of the oil with temperature. It has also been found that the efficiency may be lowered by the

presence of too much lubricant in the gear-box. In studying the conditions under which the highest efficiency was obtained with worm gearing it was proved that a certain perceptible tooth-clearance was advantageous; the said best clearance in an ordinary motor-car gear appears to be about $\frac{1}{64}$ in. (somewhat less than $\frac{1}{2}$ mm.).

Another important fact deduced was that in the saddle worm designed by Mr. Lanchester the efficiency is best with quite heavy loading; there is virtually no falling-off in efficiency due to overloading—at least unless carried far beyond the point at which the bronze slowly yields.

Further it was noted that the heavier loads are carried with the best results at high speeds of revolution.

*Spur and Bevel Gear Testing Machine.*—It will be observed that the principle involved in the Lanchester machine of measuring the ratio of the torques of the driving and driven shafts is not applicable when the shafts are parallel. Dr. Stanton has, however, succeeded in designing

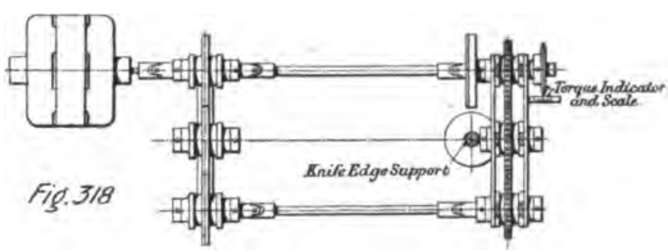


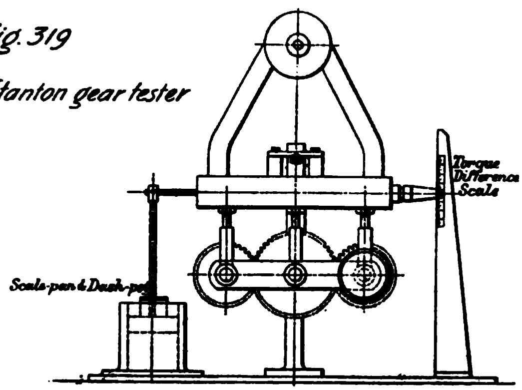
Fig. 318

a machine for this case in which the efficiency is obtained by a measurement of the *difference* of the torques together with an estimation of one of the torques separately. The machine described below is only of about one horse-power capacity in order to demonstrate the value of the principle to be employed in the proposed construction of a large machine. It was presumed that experience in the use of the small machine would bring to light difficulties which had not been anticipated, and which, if found to exist in the large machine, might be very expensive to remedy. This small machine as arranged for the test of a spur gear is illustrated in plan in Fig. 318 and in elevation in Fig. 319. It will be seen that the frame carrying the gears under test is entirely supported by a horizontal knife-edge and that both driving and driven shafts are provided with universal joints at each end. In this way it is possible for the frame to execute small oscillations in a vertical plane about its neutral position. The adoption of an intermediate wheel is rendered necessary by the fact that in order that the reaction on the frame should be equal to the difference on the torques on the driving and driven shafts, it is essential that the shafts should rotate in the same direction. When rotating in

opposite directions the reaction would be the sum of the torques, the measurement of which to the degree of accuracy here obtained is, as explained above, of no value for the purpose of an accurate determination of the efficiency. The frame is provided with an oil dash-pot for damping the oscillations and a scale pan and scale for measuring the torque difference. The torque indicator for the driving shafts is of novel design, and is shown in the right-hand corner of Fig. 318. The torque is transmitted from the driving shaft to the first wheel of the gear by means of two coiled springs in the box $A$. These springs are of equal dimensions, one left-handed and one right-handed, and thus it will be observed that a pure couple is transmitted. The driving shaft is continuous through the wheel, as shown, and terminates in an enlarged portion on

Fig. 319

Stanton gear tester




which a double spiral groove of 2-in. pitch is machined. This is a good sliding fit in an outer sleeve fixed to the gear-wheel and rotating with it and which carries the torque indicator. This sleeve is provided with two longitudinal slots in which the two studs attached to the torque indicator slide, the inner ends of the studs projecting into the grooves of the spiral and being provided with hardened steel rollers. It will be clear that the relative motion of the spiral groove attached to the driving shaft and the outer sleeve attached to the gear-wheel will cause an axial motion of the torque indicator, and that by calibration the value of the torque can be read off on the scale shown when running. It was found that this torque indicator worked extremely smoothly and with very little hunting.

The arrangement of the power circuit will be clear from the diagrams. For the return of the power from the driven shaft to the driving shaft a friction drive is employed. The two outer wheels are of cast-iron and have a velocity ratio about 5 per cent greater than that of the gear under test. The bearings of these wheels are carried by rocking-arms, which

give freedom of movement in the vertical plane about pin-joints in the supporting bracket. The intermediate wheel is of red fibre, and is carried in a similar bearing, which is fixed to the supporting bracket. The hinged bearings are connected by a steel rod passing through the forks. The tension in this rod can be adjusted by means of a wing-nut, the elasticity of the connection being supplied by the insertion of a beam-spring at one end of the rod. By varying the tension in this rod the power passing through the gear can be varied over a fairly wide range, the upper limit of which will, of course, depend on the limiting frictional resistance of the fibre wheel. In making a test, the most convenient method is to place weights in the scale pan corresponding to a given torque difference, and then to regulate the tension in the rod by means of the wing-nut until the frame is exactly balanced with the pointer at the zero of the torque difference scale. A reading of the torque indicator will then give all the data for the determination of the efficiency. It is obvious that three gear-wheels of the same tooth module are necessary.

A test on a set of mild steel wheels cut with B. and S. standard involute teeth of the dimensions stated, gave the results recorded below :

Driving and driven wheels : diametral pitch, 14 ; number of teeth, 60 ; pitch diameter, 4·286 in.

Intermediate wheel : diametral pitch, 14 ; number of teeth, 75 ; pitch diameter, 5·357 in.

Revolutions of shaft, 1230 per minute.

Measured torque in driving shaft, 4·28 ft.-lb.

Difference of torque in driving and driven shafts, 0·88 ft.-lb.

Horse-power transmitted, 1.

From these observations the torque in the driven shaft is seen to be 3·40 ft.-lb., and the combined efficiency of the three wheels is 79 per cent, giving an efficiency of transmission for each pair of wheels of 89 per cent.

It is obvious that the machine can be easily adapted for the testing of chain drives.

## REFERENCES

### *Indicators*

Reynolds. "Indicators," *Proc. Inst. C.E.*, p. 1. 1885.

Brightmore. "Indicators," *Proc. Inst. C.E.*, p. 20. 1885.

——. "Crosby-Hopkinson Comparison Test," *Proc. Inst. Mech. Eng.*, p. 785. 1909.

Stewart. "Indicators," *Proc. Inst. Mech. Eng.*, Pts. I and II, p. 7. 1910.

Hopkinson. "On the Indicated Power and Mechanical Efficiency of Gas Engines," *Proc. Inst. Mech. Eng.*, Pt. IV. 1907.

Burstall. "Indicating of Gas Engines," *Proc. Inst. Mech. Eng.*, p. 785. 1909.

Dalby and Watson. "Optical Indicator for Steam and Gas Engines," *The Mechanical World*, March 13th, 1914.

*Torsion Dynamometers*

Hirn. *Les Pandymomètres.* Gautier Villars, Paris. 1876.

Jervis-Smith. *Phil. Mag*, Feb.., 1898.

Denny. *Instit. Naval Architects*, March, 1907.

Föttinger. *Schiffbautechnische Gesellschaft*, 1903.

Broughton. *Electrician*, Dec., 1913.

Lux. *Engineering*, p. 715. 1911.

Johnson. *Engineering*, p. 605. 1911.

Gibson. "Effect of End Thrust on Torsion Measurements," *Trans. Inst. Naval Architects*, p. 126. 1907. "Torsion Meters," *North-East Coast Institution of Engineers and Shipbuilders.*

Denny. "Torsion Meters as applied to the Measurement of Power in Turbines and Reciprocating Engines," *Trans. Inst. Naval Architects*, 1907.

*Transmission Dynamometers*

Morin. "Power Measuring Machines," *Notions Fundamentales de Méchanique.* Paris. 1855.

Easton and Anderson. *Proc. Instit. Mech. Eng.*, 1876.

Jervis-Smith. *Phil. Mag.*, Vol. XV., p. 87.

Boys. *Proc. Roy. Institution*, p. 241. 1883.

Parsons. *Proc. Inst. Mech. Eng.*, 1877.

Kapp. "Dynamometers," *The Electrician*, 1884.

Amsler. *Proc. Inst. Mech. Eng.*, p. 603. 1911.

Moore. "Direct Reading Electrical Dynamometer," *Electrical World* (New York), p. 449. 1912.

*Cradle Dynamometers*

Jervis-Smith. "Ergometer for Small Electrometers," *Dynamo-Electric Machinery*, p. 384. 1884.

Brackett. *Electrical World* (New York), Jan., 1884.

Drysdale. "The Testing of Electric Generators and Motors," *Engineering*, Nov., 1905; *Electrician*, p. 517. 1910.

Davis and Shaw. *Inst. Elect. Eng.*, Manchester Students' Section, April, 1910.

Watson. *Proc. Inst. Auto. Eng.*, Nov., 1912.

*Eddy Current Dynamometers*

Morris and Lister. "The Eddy Current Brake for Testing Motors," *Journ. Inst. Elect. Eng.*, p. 445. 1905.

Pasqualini. *Fortschritte der Physik*, p. 421. 1892.

Grau. *Electrotechnische Zeitschrift*, p. 265 (1900); p. 467 (1902).

Rieter. *Electrotechnische Zeitschrift*, p. 195. 1901.

——. *Electrotechnische Zeitschrift*, p. 83. 1905.

Feussner. *Electrotechnische Zeitschrift*, p. 608. 1901.

Siemens and Halske. *Nachrichten*, No. 32. 1902.

*Machine Tool Dynamometers*

Nicholson. "Experiments with a Lathe Dynamometer," *Proc. Inst. Mech. Eng.*, p. 883. 1904.

Mallock. *Proc. Roy. Soc.*, Dec., 1881.

Benedict and Lukens, "An Investigation of Twist Drills," *Bulletin No.* 103 *of the University of Illinois*, 1917.

*Fan Dynamometers*

Walker, W. G. "Fan Dynamometer," *Engineer*, p. 297. 1911.

White and Poppe. "Fan Dynamometer," *Automobile Engineer*, Aug., 1910.

Renard. "Moulinet Dynamométrique," *Comptes Rendus d'Acad. des Sciences*, May 2nd, 1904.

Morgan and Wood. "Fan Dynamometer," *Proc. Inst. Auto. Eng.*, Vol. VII., p. 530.

Hodgson. "Some Notes on the Fan Dynamometer," *Proc. Inst. Auto. Eng.*, p. 301. 1915–16.

*Absorption Dynamometers*

Alden. "Fluid Friction Brake for Testing Water Turbines," *Trans. Amer. Soc. Mech. Eng.*, Vol. XXXII, April, 1910.

——. "Absorption Dynamometer," *Electrical World*, (New York), p. 945. 1908. *Trans. Amer. Soc. Eng.*, Vol. II.

Beaumont. "Friction Brake Dynamometers," *Proc. Instit. Civil Eng.*, Vol. XCV., Pt. I. 1888–9.

Morin. "*Notice sur divers Appareils Dynamometrique*," 1841.

Unwin. "Flexible Band Dynamometer," *British Association*, Section G., 1883.

Sankey and Wingfield. "Modification of Thomson Rope Brake," *Engineering Magazine*, Nov., 1904.

——. "Friction Brake," *Engineering*, April 17th, 1903.

Scheibe. "Compensated Belt Dynamometer," *Electrical World* (New York), p. 520. 1907.

Froude. "On a New Dynamometer for Measuring the Power delivered to the Screws of Large Ships," *Proc. Inst. Mech. Eng.*, July, 1877.

——. "Dynamometer," *British Association*, 1877.

Reynolds. "Hydraulic Dynamometer," *Collected Scientific Papers*, Vol. II., p. 353.

Reynolds. "Mechanical Equivalent of Heat," *Trans. Royal Society*, Series A, 1897.

Griffin, "Dynamometer," *Engineering*, Feb., 1912; *Internal-Combustion Engineering*, Jan., 1914.

—— "Electrical Dynamometer," *N.P.L. Report*, 1910.

*Gear Testing Dynamometers*

Lanchester, F. W. "Worm Drive Dynamometer," *Proc. Inst. Auto. Eng.*, Vol. VII., p. 238. 1912–13. *Engineering*, Aug. 27th, 1915.

Stanton. "Spur and Bevel Testing Machine," *Engineering*, p. 334, March 12th, 1920.

—— Discussion on "Oiliness and Lubrication," *Proc. Phy. Soc.*, Feb., 1919.

*Miscellaneous*

——. "Relation of the Horse-Power to the Kilowatt," *Bull. Bur. Stds.*, No. 34.

Perry. "Laws of Fluid Friction," *Proc. Phy. Soc.*, Vol. XII.

# CHAPTER VIII

## THE MEASUREMENT OF TEMPERATURE

THE importance of temperature control in industrial operations needs no emphasis at the present day, and in this chapter it is proposed to review briefly the various types of pyrometers and their application under the varied conditions encountered in practice.

### I. MERCURY THERMOMETERS

Suitably protected mercurial thermometers are admirably adapted for the majority of the temperature observations required in connexion with steam plants and for most other work in which only moderate temperatures are dealt with.

They are obtainable with scales covering various ranges of temperature between $-30°$ C. ($-2°$ F.) and about $550°$ C. $\equiv$ ($1020°$ F.). For temperature measurements above $250°$ C. it is advisable to employ the nitrogen filled type in which the upper portion of the stem and capillary is filled with inert gas under pressure. Besides raising the boiling-point of the mercury the gas pressure above the mercury surface prevents the column breaking up when the thermometer is exposed to shock or vibration.

A convenient type of thermometer for general use is shown in Fig. 320. It will be observed that the thermometer is encased in a drawn steel tube, into which it is securely cemented at each end.

For permanent installations, such as the determination of temperatures in connexion with condensers, economisers, flue gases, etc., the type illustrated in Fig. 321 is particularly well adapted. The stem of the thermometer is rigidly held in the stuffing-box, to which are screwed both the bulb chamber and the scale case. The bulb chamber *B* is turned out of a solid piece of steel and tapered to fit a socket screwed into the pipe or tank. The space inside the bulb chamber *C* around the bulb *A* is filled with mercury, which serves as a conducting medium for the heat and renders the thermometer sensitive to sudden changes of temperature.

A socket is screwed into the pipe and the hole in the socket must be accurately bored and reamered to fit the corresponding taper stem of the thermometer, in order that good thermal contact is maintained between the two under working conditions.

Fig. 320

*Steel Sheath Mercury Thermometers.*—A modification of the ordinary type of mercury thermometer which has been used in the industries for many years is the steel container type with Bourdon gauge. In principle the instrument is very simple. The mercury is contained in a mild steel vessel tapering off at one end to a fine drawn steel tube. This may be of any length up to fifty yards. At the indicator end the steel capillary is joined up to a flattened spiral consisting of a solid drawn steel tube with thin walls, rolled flat, the gap being only $\frac{1}{100}$ of an inch between the walls. The whole system is completely filled with mercury, then any expansion causes an uncoiling of the end of the spiral tubing. The rotary motion of this end is transferred to a pointer on the same lines as those employed in an ordinary steam pressure gauge. Such thermometers have an appreciable lag, but their robustness is a great feature when it is necessary to install thermometers on locomotives, etc., subject to excessive vibration. The important point to observe in their installation is to provide adequate protection to the capillary tube, so as to prevent the possibility of its being used as a hand-rail by the cleaners.

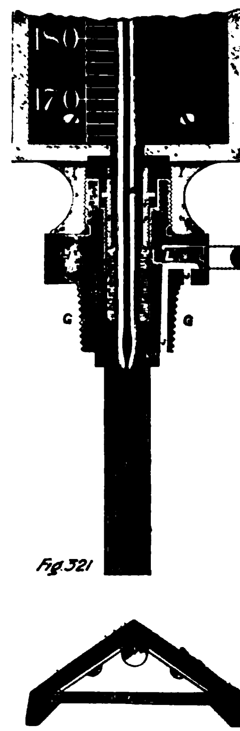


Fig. 321

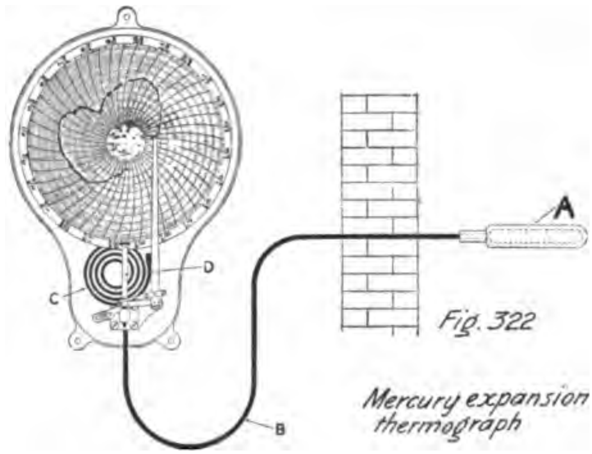
A Thermometer tube and bulb
B Bulb chamber enclosing thermometer bulb.
C Mercury bath. In the case of thermometers for temperatures above 600° F. (315° C.) special metallic packing is used instead of mercury.
D Stuffing-box with packing.
E Outside thread of bulb chamber.
H Hexagon wrench head.
I Scale case connection.
J Openings to prevent condensation inside the glass front.

Thermo-electric pyrometers are now more generally used for locomotive work since experience with the indicators has enabled them to be so constructed as to stand a considerable amount of vibration.

*Recording and Distant Reading Mercury Thermometer.*—A recording type of mercury in steel thermometer is shown in Fig. 322. The changes of pressure in the system are magnified and directly indicated or recorded by means of the pen.

The defect of this class of pyrometer is that the slightest leak in the system destroys the accuracy of the indication. Also the Bourdon tube

itself acts as a thermometer, and the temperature of the indicating mechanism affects the indication unless the system is compensated. The effect of the connecting tube may be minimized by using very fine capillary to reduce the capacity, and one manufacturer reduces this capillary still further by drawing through it a fine steel wire.

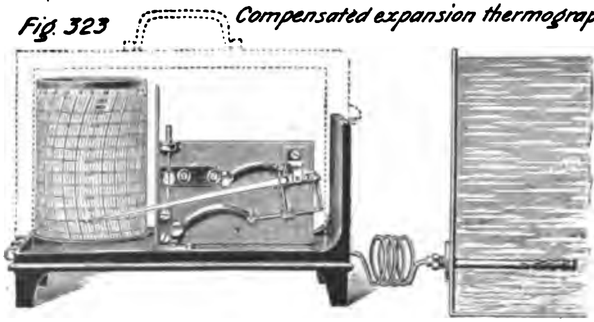



A Steel mercury bulb.
B Steel capillary tube.
C Bourdon Spiral.
D Screw for zero adjustment.

A system of compensation has been developed by the French firm of Jules Richard, which employs a secondary Bourdon tube.

The complete instrument is illustrated in Fig. 323, while the theory of the method of compensation is as follows :

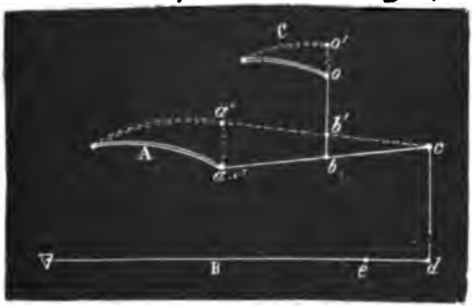
Fig. 323 Compensated expansion thermograph



In Fig. 324 $A$ is a primary Bourdon tube connected to the capillary tube and so to the sensitive bulb. One of its ends being fixed, it controls by free end $a$ the style $B$ carrying the pen, its movements being conveyed and magnified by a system of levers and links. In order that a true record may be obtained it is essential that the pen should not move, whatever change of curvature the Bourdon tube $A$ may undergo due to variations in the temperature of the surrounding air and not due to

changes in the temperature under observation. Suppose the temperature of the surrounding air rises and causes the free end $a$ to move to $a^1$, in order that the pen may not move it is necessary and it is sufficient for the point $c$ to remain stationary. That is to say, it is necessary for the change in temperature which moved $a$ to $a^1$ to move also the fulcrum $b$ to $b^1$.

Fig. 324 – Mechanism of Richards Compensated thermograph




This is done by providing a suitable compensating tube $C$, the effect of which will be evident from the diagram. To obtain correct compensation the movement of $C$ must be to the movement of $A$ as $\frac{bb^1}{aa^1}$, that is as $\frac{bc}{ac^1}$. In practice this result is obtained satisfactorily.

A pyrometer resembling the previous one is the vapour pressure type, illustrated in Fig. 325. In this the expansive fluid is ether. The bulb is

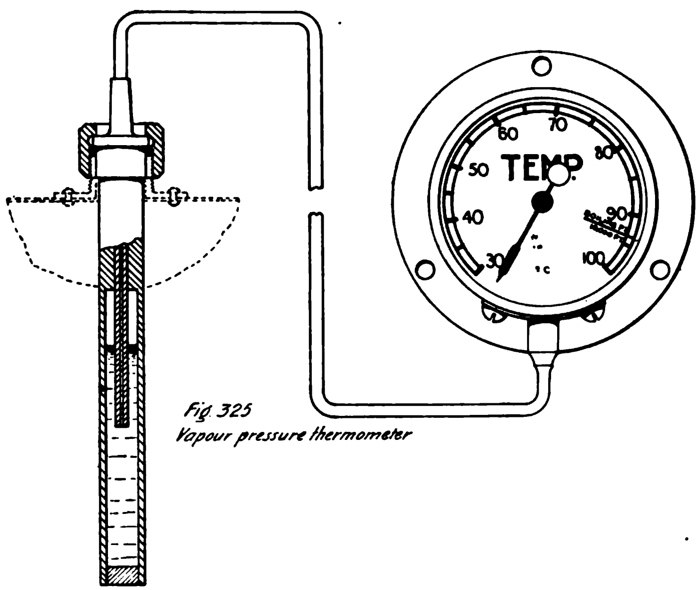



Fig. 325
Vapour pressure thermometer

about three-quarters filled with liquid, while the capillary tubing and gauge is entirely filled.

Before sealing the system is carefully freed of air, so the pressure on the surface of the liquid is that of the saturated vapour at that temperature. The indications of the instrument are not liable to error due

to "stem correction," owing to the fact that it is the saturation pressure which is being measured; also the quantity of liquid does not affect the calibration, provided the bulb and tube are not completely filled at any working temperature.

It is essential, however, to avoid heating any portion of the capillary to a higher temperature than the bulb since the instrument will indicate the saturation pressure corresponding to the maximum temperature at any point in the circuit.

Another drawback is that the temperature scale is not uniform since the vapour pressure increases more rapidly than the temperature.

A fundamental point in connexion with all types of transmitting thermometers employing a non-compensated Bourdon gauge for indicating the pressure changes is the fact that the gauge indicates the difference between the pressure of the fluid and that of the surrounding atmosphere.

In the case of the vapour pressure thermometers the internal pressure is not large compared with the atmospheric pressure, consequently the indications are affected by ordinary barometric changes to a slight extent when used at various altitudes, as in the case of aircraft instruments.

The data in the table below show the changes in the case of the ether-filled type:

| True Temp. | Instrument Reading | |
|---|---|---|
| | Height, 10,000 ft. | Height, 20,000 ft. |
| 50° | 55·8° | 59·7° |
| 80° | 82·9° | 85·0° |
| 100° | 102·0° | 103·4° |

When the difference in level between the bulb and the gauge is considerable, this has also to be taken into account.

*Low Temperature Thermometers.*—Thermometers similar to the standard type of mercury thermometers, but filled with pentane instead of mercury, will measure temperature down to $-190°$ C., and are very useful in connexion with liquid air plants.

For distant reading purposes the resistance thermometer is the most suitable and is now being extensively used in connexion with technical plants for the production of liquid air and oxygen.

*Linear Expansion Pyrometers.*—Another simple expansion thermometer which has been used for high temperatures is based on the differential expansion of iron and graphite. An iron tube encloses a graphite rod, and the difference in expansion on heating is multiplied

up by means of suitable levers to operate the pointer around the scale.

These pyrometers, of course, indicate the mean temperature over the length of the furnace occupied by the rods, and as used, are moderately reliable. Their accuracy is, of course, less than that of the other types of pyrometers which are described.

*Calibration of Thermometers.*—Mercurial and vapour pressure thermometers can be used for the measurement of temperature over the range $-30°$ C. to 400° C., and if suitable precautions are taken in their installation and maintenance they can be relied upon to give accurate information.

It is desirable to check the indications occasionally by means of a calibrated thermometer, and this can generally be done with the pyrometer in its permanent position.

If the conditions do not admit of a comparison over an extended range of temperature then recourse must be made to a stirred water or oil bath.

One condition should be strictly observed in the calibration of thermometers of the exposed stem type, such as ordinary mercurial thermometers and the transmitting form completely filled with mercury or other liquid, namely, to give the same depth of immersion to the thermometer during comparison as prevail under service conditions. A variation in the length of the emergent column of 150 degrees at 450° C. for mercury in a glass thermometer produces a change of 10 degrees in the reading.

## II. Thermo-electric Pyrometers

Thermo-electric pyrometers are extensively used in the industries for the control of furnace temperatures. If suitably constructed they are well adapted for ranges up to 1200° C. =(2190° F.).

A thermo-electric pyrometer consists essentially of two dissimilar metals joined together at one end, and connected at the other ends to the terminals of a galvanometer. If the two ends of the dissimilar metals be at different temperatures, an electric current will flow in the circuit and will deflect the galvanometer by an amount approximately proportional to the temperature difference.

In Fig. 326 a simple thermo-electric circuit is shown. Two dissimilar metals are joined together at $A$, and at the other end $C$ they are connected by a pair of leads to a galvanometer. The end $A$ is inserted into the region whose temperature is desired, whilst the end $C$ remains approxi-

mately at room temperature: the difference of temperature between $A$ and $C$ is shown by an appropriate scale on the galvanometer.

Fig. 326

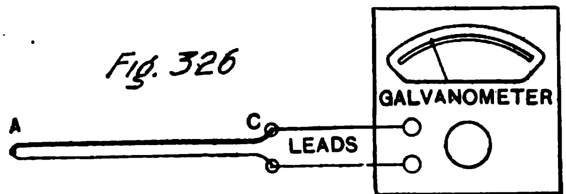
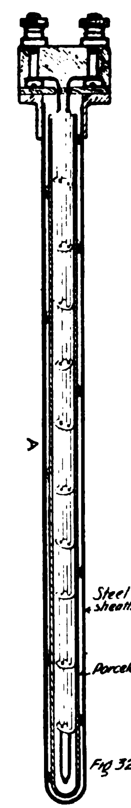



Diagram of thermocouple.

*Metals suitable for Thermojunctions.*—Le Chatelier, who made a careful investigation of the subject, came to the conclusion that platinum versus platinum 10 per cent rhodium were the most suitable combination for a thermojunction from the point of view of reliability and of possessing a sufficiently high melting-point to be used at high temperatures.




Thermocouples of these metals are consequently in general use, but the material is costly and requires careful protection from metallic fumes and reducing gases.

A common form of mounting is illustrated in Fig. 327.

The two wires are autogenously fused together at the hot end, insulated by fire-clay and mica washers and enclosed in a glazed porcelain or silica sheath. This is protected from mechanical injury by another sheath of steel.

Besides the costly nature of the material the rare metal thermocouples have another disadvantage, insomuch that they require an indicator of comparatively high resistance to "swamp" any effect on the total circuit resistance of changes due to varying depths of immersion of the couple in the hot region.

Sensitive high resistance indicators are delicate instruments, ill-adapted to withstand rough usage, consequently a number of manufacturers have tackled the problem of producing a robust pyrometer outfit employing combinations of metals which give a large thermo-electric effect and which are also cheap.

The most generally used combination for low temperature work (i.e. up to 800° C. = 1472° F.) are iron constantan,[1] the latter alloy consisting of 60 per cent copper and 40 per cent nickel. These metals not being costly can be used in the form of stout wires, as illustrated

[1] Also known as "Eureka."

in Fig. 328, or in the form of a rod welded to an iron tube, as shown in Fig. 329.

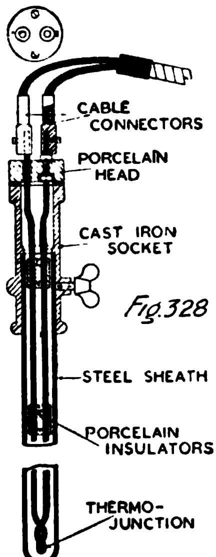



Fig. 328
Base metal thermoelement

To reduce the effect of oxidation it is advisable to use wires of heavy cross-section, and this has the further advantage of reducing the electrical resistance.

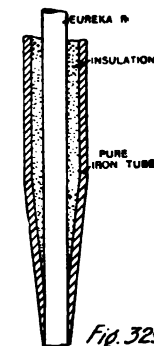



Fig. 329
Junction of iron-eureka thermoelement

In Table XI some figures are given for the electromotive force generated by junctions of various combinations of metals. It must be remembered, however, that the precise value depends on the purity and physical state of the material, so that the data can only be regarded as approximate.

*Thermocouple Protection Tubes.*—The material to be used for the sheath of a thermo-element is determined by the conditions as regards temperature and oxidation. To withstand low temperature work a strong iron pipe is used, on account of its cheapness. Its defect is that it is readily oxidisable. Nichrome will stand higher temperatures, but is, of course, more expensive. When platinum alloy couples are used it is essential to protect them fron contaminating effects of metallic vapours and consequently a

TABLE XI

| Thermo-elements | E.M.F. in millivolts at 500° C. |
|---|---|
| Platinum : platinum 10 per cent rhodium | 4·4 |
| Platinum : platinum 10 per cent iridium | 7·4 |
| Nickel : nickel 10 per cent chromium . | 10 0 |
| Iron : nickel . . . . . | 12·0 |
| Iron : constantan . . . . | 26·7 |
| Silver : constantan . . . | 27·6 |
| Copper : constantan . . . | 27·8 |

porcelain or a quartz sheath is invariably used around the couple. For the mechanical protection of this, an iron tube is frequently utilised. Porcelain certainly offers the maximum protection from contaminating gases, but will not stand sudden temperature changes in the same way as quartz. Rapid heating and cooling to temperatures of 1100–1200

centigrade causes devitrification of quartz and a loss of mechanical strength.

In recent years attempts have been made to devise sheaths composed principally of carborundum. These are known by a variety of trade names, such as silfrax, etc. They are not gas-tight, consequently an inner sheath non-permeable to gases has always to be employed. When thermo-elements are employed for taking the temperatures on molten alloys, such as aluminium, it is advisable to protect the tube by a graphite sheath.

*Indicators for use with Thermocouples.*—For industrial work direct reading indicators are largely favoured for use with thermocouples. Essentially an indicator consists of a sensitive moving coil constructed on exactly the same principles as those employed on switch-boards. The maximum electromotive forces available are only of the order of about 14 millivolts for platinum alloy thermocouples and 50–60 millivolts for base metals. For use with platinum alloy thermocouples it is essential that the indicator should be of high resistance, otherwise the variation in the resistance of the circuit will affect the reading. High sensitivity and high resistance are somewhat conflicting conditions in a moving coil instrument. But by systematic improvement of details manufacturers are now able to supply indicators suitable for use with platinum alloy thermocouples with resistances of several hundred ohms. Since the couple wires themselves are only a few ohms in resistance, variations in these due to different depths of immersion in the hot region, etc., are of no consequence.

*Temperature of Cold Junction.*—It will be observed that in the thermo-electric method of pyrometer it is the *difference of temperature* between the "hot" and "cold" junctions which is measured. If the cold junction remains at room temperature all that is necessary is to add the temperature of the cold junction to the reading, or preferably set up the pointer of the instrument by this amount when on open circuit. In industrial work, however, the temperature of the cold junction is far from constant and consequently it is desirable to employ some method of minimizing or eliminating these fluctuations.

One of the simplest and commonest is to employ leads of the same material as the couples when these are of base metal. The effect of this is to transfer the cold junction from the heat of the furnace to the indicator, which is generally situated in a more favourable position as regards constancy of temperature.

In the case of platinum alloy thermocouple leads of the same material

would be too costly, but the same result can be obtained by using leads of copper and a special alloy of copper and nickel, giving for ordinary ranges of temperature the same electromotive force as the platinum and platinum alloy of the couple.

It has been found by experiment that such leads will compensate for any temperature of the cold junction up to 300° C. Variations of temperature at the indicator can be compensated for by an arrangement due to Darling in which a bimetallic spiral strip is used to move the pointer of the indicator.

In this arrangement a Breguet spiral is fixed at its upper end and coupled below to the zero setting device which carries the control spring. Any rise of temperature which affects the cold junction also affects the Breguet spiral and causes the pointer to move up the scale. When the indicator is disconnected, the position of the pointer on the scale corresponds to its temperature.

Another method for reducing the fluctuations due to changes of room temperature is to bury the cold junction several feet below the surface of the ground. At a depth of 10 feet the maximum seasonal variation of temperature only amounts to 5° C., while under cover of a large building artificially warmed in winter the oscillations may be as little as 1½ degrees.

In the application of this method an auxiliary couple identical in its thermo-electric properties with those of the couple employed in the furnace is inserted into a pipe driven into the soil. The free ends of both primary and auxiliary couples are run into a junction box.

When the cold junction of the primary couple gets hotter for any reason, the junction of the auxiliary couple contained in the same box is subjected to the change. Hence if the ends in the junction box are so connected that the voltage change of each opposes that of the other in the circuit compensation will be obtained. It will be observed that the fundamental basis of the method is the assumed constancy of the earth temperature, and this would require careful investigation if a large furnace were situated in the vicinity of the buried junction.

*Calibration of Thermo-electric Pyrometers.*—In the maintenance of a pyrometer installation under industrial conditions the tests necessary may be considered under two heads :

(1) The primary calibration of the outfit.

(2) The verification of the accuracy of the observations periodically under working conditions.

The primary calibration can best be done with the specialised equipment of a standardising institution possessing a number of master standards which have been calibrated in terms of the International Scale of Temperature. In large installations it is advisable to keep one pyrometer as a check standard. This should be used with a high resistance indicator—of the order of 200 ohms—or better still, a portable potentiometer. Such an outfit will necessarily be more delicate than the industrial outfit and should be handled with care.

Probably the most important test of all from the practical point of view is the checking of the outfit under working conditions, and this can be effected with the standardised couple and indicator or portable potentiometer.

It is not sufficiently realised that a base metal couple may develop heterogeneity after prolonged exposure to high temperatures, this being due to structure changes in the alloy. Under these circumstances the readings obtained will depend upon the depth of immersion and the temperature gradient since the values are affected only when the heterogeneous part is in a region with temperature gradients. Hence it is essential that the conditions of test should correspond closely to those obtaining in actual practice, and this can be effected by inserting the test couple into the furnace alongside the other with the hot junctions in close proximity. Observations should be taken at a series of temperatures. If the conditions prevailing in the furnace are fairly definite and the heterogeneity effect small consistent values should be obtained for the difference between the two thermocouples. If, however, the differences are of variable magnitude and not reproducible it would be advisable to discard the thermocouple.

It is, of course, useless to expect the same accuracy in a test of this character as would be obtained under laboratory conditions, but the data should show beyond doubt the accuracy of the temperature observations. It is advisable to use as check couple one of small cross-section and protected by a thin tube. It would then serve to show whether the depth of immersion of the working thermocouple is sufficient. When heavy iron protecting tubes are employed it may happen that the conduction along the tube is so considerable as to keep the temperature of the hot junction below that of the region into which it projects.

When low resistance indicators or recorders are employed it is important not to have any changes in the resistance of the circuit after the calibration has been effected.

Errors of as much as 50° C. have been found due to oxidation of

the wires of the couple, although the E.M.F. was quite unaltered when measured on a potentiometer.

## III. Resistance Thermometers

The change in the electrical resistance of platinum, with temperature as a method of measuring temperatures, was employed by Siemens in 1871. The later researches of Callendar and Griffiths brought this method to a very high degree of precision, and at the present time it is the method almost universally adopted for refined scientific work. The thermoelectric method lacks sensitivity for low temperature work, and there is the inherent difficulty as to cold junction temperature.

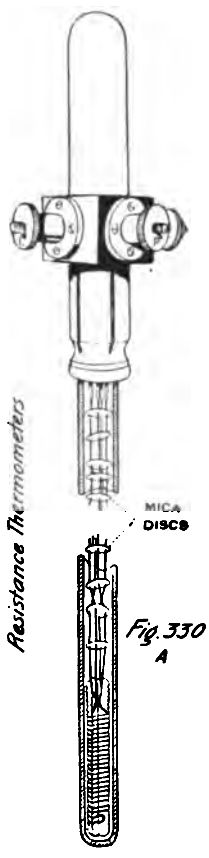



Fig. 330 A

The resistance thermometer indicator can be designed to give a full scale deflection for a narrow range (as little as 50° C.), and consequently is well suited for taking cold stores' temperatures, etc., where observations to better than one degree are desired. It has the disadvantage, of course, that a battery is necessary, and for deflectional methods the current through the bridge must be adjusted from time to time to a specified value.

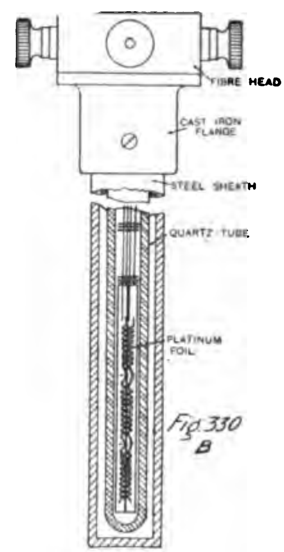



Fig. 330 B

*Whipple Indicator.*—In the Whipple indicator the observer obtains a balance on a Wheatstone's bridge, and as the method is a "null" one, constancy of current or of galvanometer sensitivity is immaterial with this instrument. The bridge wire is wound on a drum which the observer rotates until the needle returns to zero, and the temperature can be read off from the position of the drum.

*Construction of Resistance Thermometers.*—In laboratory resistance thermometers the platinum wire is wound on serrated mica racks and the same practice is adopted in some technical types. (See Fig. 330 *A*.)

Another form has the platinum coil wound in long spirals of platinum foil, fixed in the angles of a mica cross (Fig. 330 *B*). The advantage claimed for this method of construction is that the platinum is not strained when the mica swells after exposure to high temperatures. High

resistance thermometers, such as are used for taking the temperature of cold stores have the platinum wire wound on a glazed porcelain tube and fixed in place by hard varnish.

*Electric Transmitting Radiator Thermometer.*—An interesting type of resistance thermometer outfit, embodying the principle of the ohmmeter, is used on a German aircraft for indicating the temperature of the water in the engine radiators—the pyrometer being connected to the indicator fixed on the instrument board. The particulars given were obtained from measurements of a captured instrument.

The resistance thermometer is made of platinum wire, wound on a strip of micanite. The coil is enclosed in a flat copper tube, forming

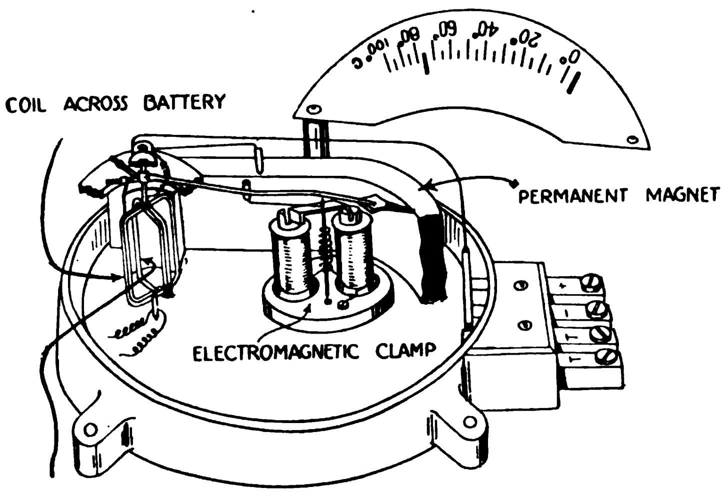



Fig. 331

part of a brass elbow, screwing into the radiator. The resistance of the thermometer coil at zero centigrade is about 90 ohms ; this high resistance is desirable in view of the fact that no compensation is applied for the change in resistance of the connecting leads, and the variation in these leads would be important with a low resistance thermometer. A push-button switch forms part of the equipment, so that the current is only used during the actual observation.

The indicator (Fig. 331) is a miniature form of the well-known simple ohmmeter ; it is based on the moving coil principle. The two coils are wound crosswise on the same aluminium frame, and move freely in a powerful magnetic field. One coil is connected through a resistance across the battery (see Fig. 332), and circuit connections may be traced from the battery by conductors 1 and 10, resistance 11, conductor 12,

coil 13, conductor 7, resistance 8, and conductor 9 to the battery. The other coil is connected in series with the resistance thermometer. Circuit connections may be traced from battery by conductors 1 and 2, resistance 3, conductor 4, through the thermometer, by conductor 5, coil 6, conductor 7, resistance 8, and conductor 9 to the battery.

The indication is thus the ratio of $\dfrac{\textit{electromotive force}}{\textit{current}}$, that is, the resistance of the thermometer circuit. The reading is theoretically independent of the pressure employed, but actually the E.M.F. must be kept within limits: otherwise, if the E.M.F. is too low, friction decreases the sensitivity, and if too high, the current causes appreciable heating up of the resistance thermometer above its surroundings.

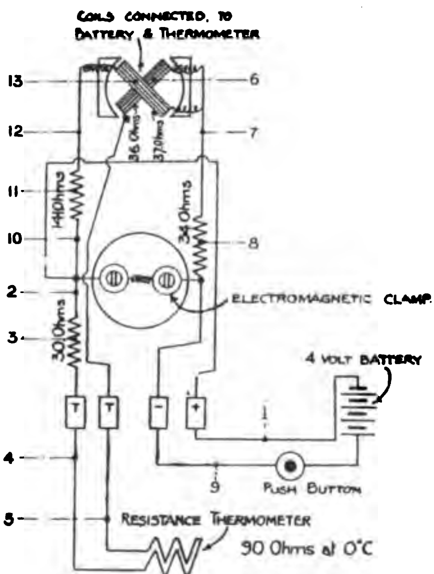



Fig. 332

DIAGRAM OF CONNECTIONS

The same rule should, in fact, be used here as in the case of the laboratory platinum thermometer, i.e. the current should always be the same value as that used in the calibration of the instrument.

It will be evident from the principle of this instrument that, owing to the absence of any control spring, the pointer always remains at a position somewhere away from the zero, depending on the last reading taken: this apparent reading would prove somewhat deceptive, and should be eliminated by some form of clamp for setting the pointer back to zero. The clamp in this particular instrument consists of a small arm, pivoted about a vertical axis, and arranged to hold the pointer at zero by the action of a spring. When the current is switched on the arm is immediately swung round to the top of the scale by a small electro-magnet, connected across the battery, and remains fixed while the reading is taken. As soon as the current is switched off again the arm is released, and returns the pointer to zero.

This device will be clear from Fig. 331. The scale of the instrument is very cramped, owing chiefly to the large angle subtended by the crossed coils (60 degrees in this case). The graduation is, moreover, not uniform, but closed up in the central part of the scale, making the

calibration somewhat troublesome. It would, of course, be an improvement to use a smaller range of temperature for the purpose of controlling the temperature of the water in the radiator, instead of 0° C. to 100° C., as in this instrument

In general it may be stated that the sensitivity and reliability of the resistance thermometer makes it especially suitable as a check standard, although for general works use for high temperature measurement it is less convenient than the thermo-electric type of pyrometer.

## IV. Radiation Pyrometry

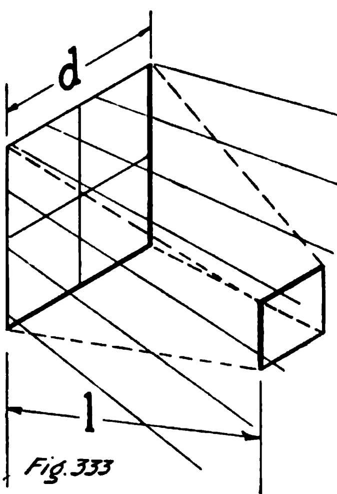
It is obviously an immense convenience for high temperature work if the temperature can be determined without submitting the pyrometer to the extreme temperature which has to be measured, and it is on this account that Féry and optical pyrometers are of such value in industrial work. It is a well-known fact that the light emitted by a hot body depends upon the nature of its surface. For example, a piece of polished platinum and a piece of carbon although at the same temperature will not appear equally bright, and it might at first sight appear that the utilisation of the heat or light emitted by an object as a method of measuring its temperature would be exceedingly complicated. Experimental researches in Physics, however, have shown that the relation between the heat emitted from a surface and its temperature is a very simple one when that surface is dead-black. This implies a somewhat ideal surface and is very different from those of ordinary metals; untreated carbon is a very close approach to such a surface. It was discovered, moreover, that the radiation projected out from a hole in an enclosure, such as a furnace uniformly heated, was very nearly equal to that which would be emitted by a perfectly black surface. This is a discovery of fundamental importance, both theoretically and practically, since it permits of the application of the simple theoretical laws to the most common case in industry, namely, furnaces or muffles. Of course, it is not always permissible to assume that the walls of a furnace are absolutely uniform in temperature, but the influence of departures from uniformity are of negligible importance in practical work. The two laws on which the practical pyrometers are based are generally known as Stefan's law and Wiens' law. Total radiation pyrometers, such as the Féry, are based on Stefan's law, while optical pyrometers, such as the Wanner, are based on Wiens' law. The fundamental difference between the two types being that in the one case the total emission of

heat is utilised, while in the other only the intensity of the light of one colour is used. Needless to state, the temperature indicated will be the same whichever type of instrument is employed, provided the conditions are those required by theory.

Both classes of pyrometers possesses the unique advantage that it is not necessary to subject any part of the instruments to the temperature it is desired to measure. Hence they are well adapted for the measurement of extremely high temperatures.

*Total Radiation Pyrometers.*—Considering first the "total radiation" type, in this instrument the total radiant energy which enters the pyrometer from the furnace is collected on a small receiving disc to which is attached a thermocouple. The rise in temperature of the receiving disc is a measure of the energy emitted as radiation from the furnace. Now it is obvious that for a practical form of pyrometer this rise of temperature of the disc should be a function of the temperature of the furnace and only of the temperature.

It is a well-established fact that the heat energy received by an object from a small source varies as the inverse square of the distance between the object and the source. If the source is of large dimensions, as is generally the case with furnaces, etc., it is possible to so design the pyrometer that the readings are independent, within limits, of its distance from the furnace.




It is simply necessary to limit the beam received at the pyrometer to a cone of definite angle, then, provided this cone is completely filled, the readings will be independent of the distance. Considering the diagram, in Fig. 333, it will be seen that if the distance between the receiving and the emitting surfaces is halved the area covered by the cone is reduced to one-quarter; hence the total quantity of energy received by the absorbing surface is independent of distance.

In the Foster form of radiation pyrometer, illustrated in Fig. 334, the heat radiation contained within the cone *AOB* is focussed by the small mirror *M* on to the thermocouple *S*. In the Thwing form a cone replaces the mirror and the thermocouple is situated at the apex. In both cases the thermo-element is connected to a sensitive moving coil instrument whose scale is graduated directly in temperatures.

The optical arrangement of the Féry pyrometer (Fig. 335) is different from the above insomuch that the heat rays $A$ from the furnace are received on the concave mirror $C$ and brought to a focus at $N$. Looking through the eye-piece $E$ the observer sees an image of the furnace in the

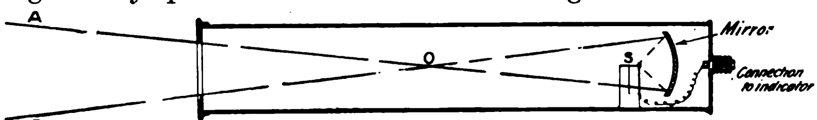



Fig. 334 Total radiation pyrometer

small mirror $M$, and is able to point the telescope on the exact spot of which the temperature is required and to focus it on that spot. The small sensitive thermocouple is situated just behind a small hole in the mirror $M$, and becomes heated by the rays passing through this hole. Where a very wide range of temperature has to be measured a diaphragm is fitted in front which can be moved in and out of position by a lever on the outside of the case. The indicator is then calibrated for two ranges, the change from one scale to the other being made by simply altering the diaphragm lever.

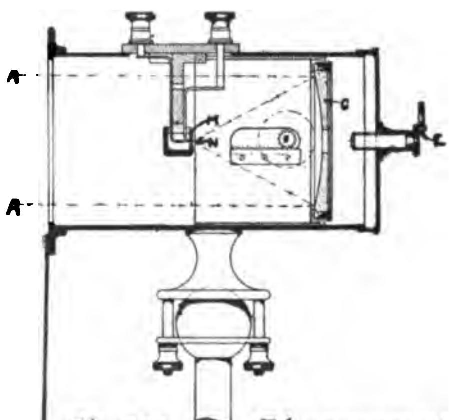



Fig. 335 Féry pyrometer

The ingenious focussing arrangement devised by Féry will be understood from Fig. 336. The function of the two small inclined mirrors is

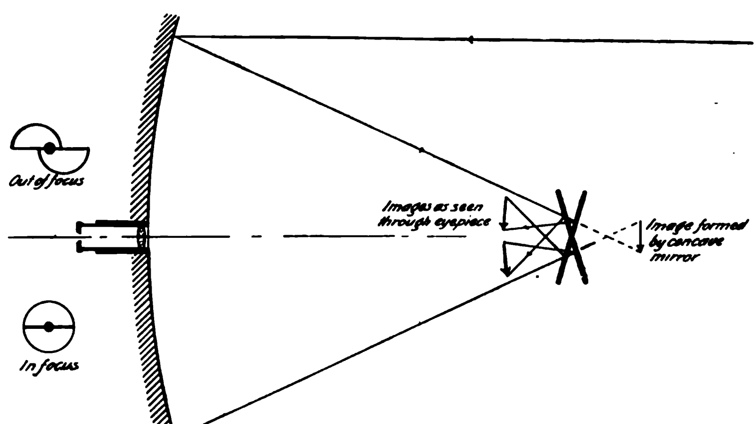



Fig. 336_ Out of focus image shown on exaggerated scale

to enable the observer to focus accurately the radiation on to the hot junction. They are in the same plane as the junctions, and from a study

of Fig. 336 it will be seen that the image of a straight line viewed through the eye-piece will appear broken unless it is formed exactly in this plane. In practice the image of the hot object will appear distorted unless in true focus.

Although the Féry type requires focussing by the observer, it has the advantage that a much smaller source will suffice for a given distance than is the case with the type illustrated in Fig. 334; also it is possible to pick out an object and sight the pyrometer directly upon it.

The above-described pyrometers require an indicator connected to the pyrometer by a pair of leads. This arrangement is frequently very inconvenient in works' practice, and to eliminate the necessity for an indicator Féry devised a special pyrometer. In this form the radiation is focussed on to a bimetallic spiral, and this controls the movement of a pointer which moves across a dial calibrated in temperature.

The instrument is identical with the thermo-electric in other respects.

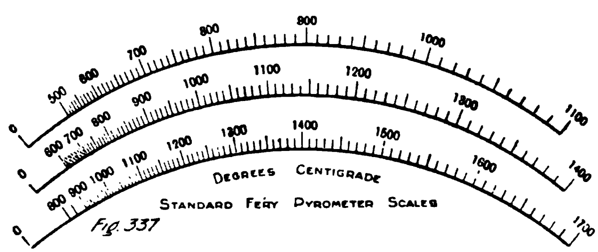


Fig. 337

The action of the spiral when heated will be understood from the following consideration. If two strips of metal having different coefficients of expansion with temperature, be soldered together to form one strip of double thickness, then, if the temperature be changed, the two sides of the strip will expand or contract by different amounts, thus causing the strip to bend. In the Féry spiral pyrometer the strip built up of two dissimilar metals is rolled flat and very thin, and coiled into a spiral shape, so that as its temperature is raised the spiral uncoils. This spiral is very small, actually measuring less than $\frac{1}{8}$ in. (3 mm.) in diameter, and $\frac{5}{64}$ in. (2 mm.) wide. It is fixed at the centre, and its free end carries a light aluminium pointer, which moves across a dial. The instrument is calibrated, so that the reading of the pointer on the dial indicates directly the temperature of the body on which the instrument is sighted.

The radiation from a furnace increases rapidly with the temperature, consequently at low temperatures it is only possible to obtain sufficient sensitivity in a portable instrument for temperatures exceeding 500° C. The manner in which the scale of the instrument opens out at high temperature is illustrated by Fig. 337.

Radiation pyrometers will not give the correct temperatures of bodies which have a low emissive power, such as polished metals, etc., consequently their application is limited to taking the temperature of uniformly heated enclosures which have the unique characteristic of radiating like a perfectly " black " surface.

When employed for taking the temperature of molten metal, the correction depends on the nature of the surface; whether oxidised or coated with slag, etc. The magnitude of possible error will be seen from the following extreme case.

The apparent freezing-point of copper obtained with a total radiation pyrometer sighted on a clear surface was found to be 600° C.—true freezing-point 1083° C. Hence the pyrometer, although it read corectly on a furnace, gave readings in error of 483° C. when used on a metallic surface.

*The Whipple-Féry Closed Tube Pyrometer for Measuring Temperature of Molten Metals, etc.*—The Whipple-Féry closed tube pyrometer is a modified form of the Féry radiation pyrometer, and is suitable for measuring high temperatures in some cases where other forms of radiation pyrometers would be unsuitable, e.g. in salt bath furnaces, in open crucibles of molten metal, etc. By the use of this instrument the actual temperature of molten metal in a crucible or ladle can be obtained, regardless of the condition of its surface.

The pyrometer consists of a long iron tube, closed at one end by a blind tube made of fire-clay, salamander, quartz of steel (to suit various requirements). This blind tube is the portion subjected to the temperature to be measured, and the rays of heat radiating from the closed end are reflected at the opposite end by a concave mirror, and collected to a focus at which is fixed a small thermocouple. An electromotive force is thereby generated in this thermocouple which is connected to an indicator, thus giving a direct reading of the temperature of the end of the tube.

The standard size has an over-all length of 5 ft. 6 in., with a tube of salamander 2 ft. long and 1¾ in. diameter. A wide flange is employed to protect the hand of the observer from the heat in the case of open crucibles. It might be remarked that it is essential to have a non-porous tube, since the presence of any fumes in the interior would seriously vitiate the observations. Owing to the heating-up of the vital parts it is not practicable to use this form for taking the temperature of large ladles of metal.

*Optical Pyrometers.*—In these instruments the intensity of the light emitted by the furnace is used for the determination of the temperature.

Since the colour of the light emitted varies with the temperature, it is necessary to employ a filter glass which transmits one colour only. Red light is usually worked with, as it is a predominant colour in the radiation at low temperatures. In the pyrometer illustrated in Fig. 338 the essential

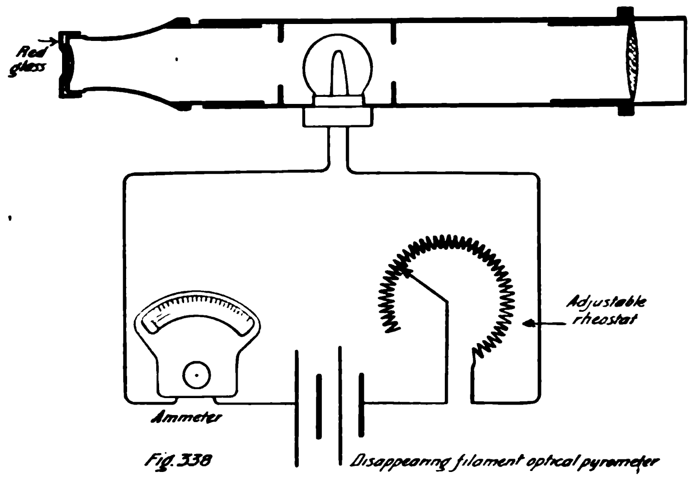



Fig. 338 Disappearing filament optical pyrometer

elements are the telescope and the filament lamp, the current through which can be varied. The image of the object sighted on is focussed in the plane containing the filament, and the temperature of this is varied until it disappears against the background. The current through the ammeter is then a measure of the temperature of the object.

Another type of optical pyrometer is shown in section in Fig. 339.

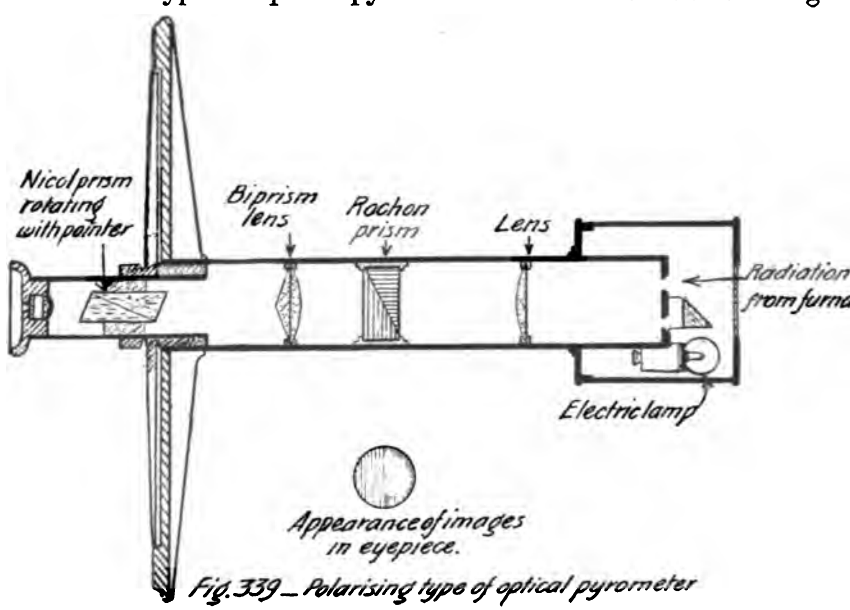



Fig. 339 — Polarising type of optical pyrometer

The intensity of the light from the furnace is matched against that of the small electric lamp, the matching being effected by rotation of the micol prism in the eye-piece. The two images consist of semicircular patches of light. By means of absorption glasses placed in front of the pyrometer the range of the instrument can be varied between 700° and 3600° C.

Although more complicated than the disappearing filament type the polarising type has the advantage of a direct reading scale and one which is not rendered worthless by the accidental breaking of the electric lamp. The electric lamp has to be matched from time to time against an amyl acetate lamp supplied with the outfit, so the ageing of the lamps can be allowed for by a slight permanent increase or decrease in the current supplied to the lamp.

The radiation type of pyrometer is more subject to error on account of imperfect " black body " conditions than the optical type, but it has the advantages that it is direct reading and can be connected to a recorder for continuous records of the temperature changes.

## V. Recorders

When it is desired to have a graphical record of the temperature changes of a furnace or other object it is customary to connect the thermo-element or pyrometer to a recording electrical instrument. These may be divided into two classes :

(*a*) Instruments which have a simple deflected pointer and marking arrangement.

(*b*) Instruments in which the thermo-electric force or resistance is balanced automatically and the instrument functions as a laboratory potentiometer or bridge employed as a "null" instrument.

The second class of instrument is considerably more complicated than the first, but has the advantage of giving results of higher accuracy since no assumption is made as to the constancy of the indicator.

It might be remarked that on account of the small forces which are involved, it is not possible to make a satisfactory recording pyrometer after the fashion of recording instruments used on switch-boards of central stations.

In instruments of class (*a*) the difficulty is overcome by allowing the pointer to move freely above the paper-chart, and depressing it at intervals by a mechanism which records its position at that instant on a moving chart.

There are numerous types of recorders for use with thermo-elements working on this principle. The one shown in Fig. 340 is made by Mr. R. N. Paul. It is operated by a small electric motor. This motor is provided with a centrifugal governor which keeps the speed constant within narrow limits. The motor tends to run too fast, this tendency being corrected by the governor, which, flying out, closes a shunt circuit across the armature and thus holds the speed constant. Power is transmitted from the motor to the recording mechanism through a reducing gear, the worm wheels of which are interchangeable, so that on occasion the speed of the chart may be altered. Each chart lasts for a period of one thousand hours, and the downward extension of the case permits of a record of two or three days' duration being seen at a glance; the chart can be re-wound in this lower detachable extension.

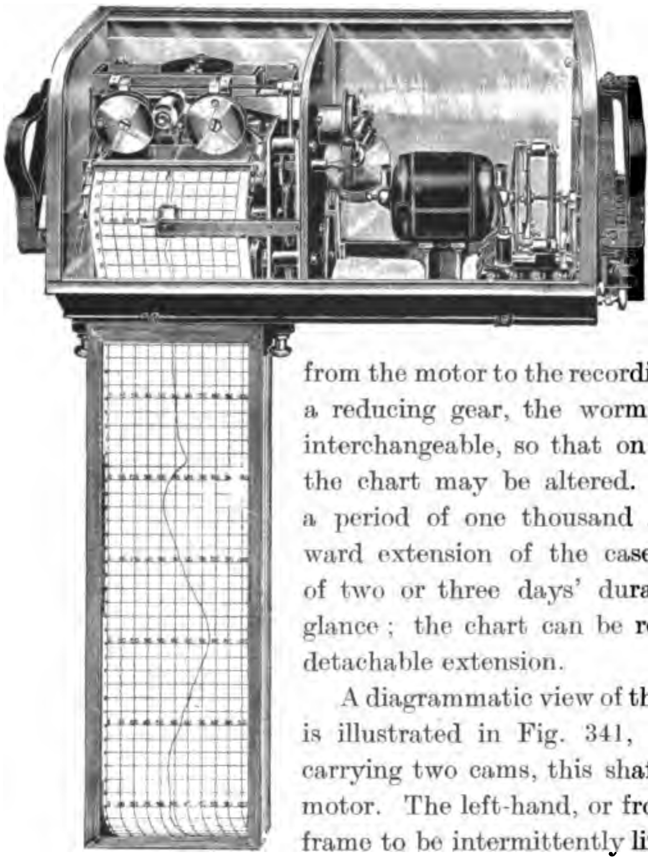
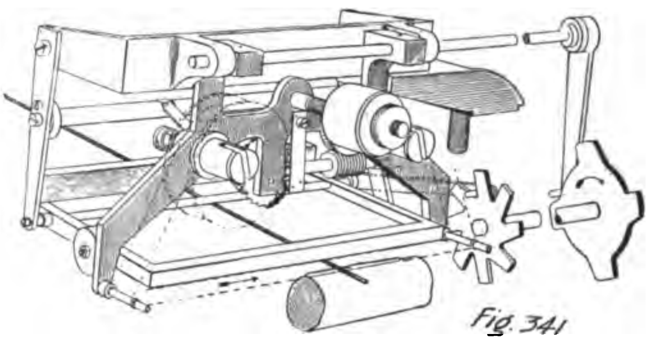


Fig. 340

A diagrammatic view of the recording mechanism is illustrated in Fig. 341, which shows a shaft carrying two cams, this shaft being driven by the motor. The left-hand, or front, cam causes a light frame to be intermittently lifted and then dropped upon the pointer, below which is a typewriter ribbon; under the ribbon lies a fixed bar having a narrow straight edge, over which the chart is continuously driven. The intersection of the pointer and straight-edge represents the point at which the mark is made. One result of this arrangement is that the ordinates on the chart are straight, and not curved, as in the case of most direct-writing recorders.

A swinging frame carries the ribbon bobbins, and the ribbon is fed intermittently from the left-hand to the right-hand bobbin at a very slow rate, so as to present always a fresh surface of ribbon for use. The swinging frame is actuated from the right-hand, or near cam, and the ribbon-feed is driven from a ratchet and worm wheel. The to-and-fro

movement of the swinging frame serves also another purpose, since, when two records or more are to be made on one chart, the typewriter ribbon has two colours ; in the case, for example, of the two records, a two-way switch is added to the mechanism, so that when the switch is on one couple the record is in black, and when on the other couple in

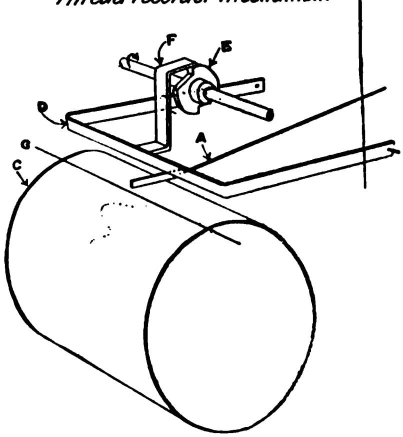



Recording mechanism, with cam-actuated tapping and rocking frames.
The dotted lines show path of ribbon.

red. A conspicuous advantage of the use of a motor in place of the more delicate clockwork commonly employed is its ability to work switches of robust construction, as the motor affords an ample margin of power.

In another type of recorder, manufactured by the Cambridge and Paul Instrument Co., the paper is fixed on a drum worked by clockwork. The galvanometer boom is depressed at intervals by a cam, as shown in Fig. 342, and presses on an inked thread.

Fig. 342
Thread recorder mechanism




The best-known instrument of class (*b*) is the Callendar recorder, which was originally developed for use with industrial forms of resistance thermometers, but can also be adapted for use as a recording potentiometer for thermocouples. This recorder is the parent of modern electrical thermometer recorders, and is essentially a clockwork-operated Wheatstone's bridge.

The instrument (see Fig. 343) consists of a Wheatstone bridge or potentiometer, in which the movement of the slider along the bridge wire is automatically effected by relays worked by the current passing through the galvanometer between the bridge arms.

According as the moving coil of this galvanometer *GC* deflects in one direction or the other, a relay circuit is completed through one or other of two electro-magnets *MM*. Each of these magnets is mounted on a clock, the movement of which is prevented by a brake. When a current

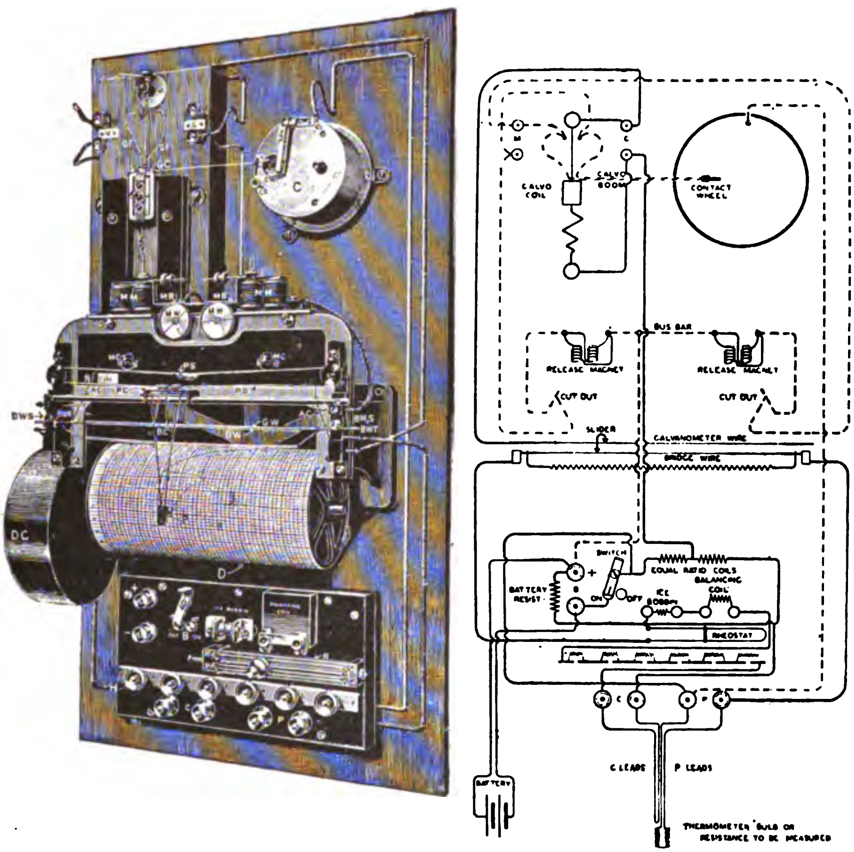



*Fig 343.— Callendar Recorder*

AC Automatic cut-outs.
BC Bridge contact springs.
BW Bridge wire.
C Contact clock.
CF Contact fork.
CS Contact clock starter.
CW Contact wheel.
D Drum carrying record sheet.
DC Drum driving clock.
GC Galvanometer coil.
GF Fine wire connections to contact fork.
GL Lifter and clamping screw for galvanometer coil.
GW Galvanometer wire.
H Milled heads to zero coils.
MB Motor clock brakes.
MC Motor clocks.
MM Motor release magnets.
MW Motor clock brake wheels
P Pen.
PC Pen carriage.
PD Pen carriage driving cord.
PS Pen carriage driving screw.
R Rheostat.
C Terminals for "C" leads.
P Terminals for "P" leads.

passes through the magnet this brake is lifted, allowing the clockwork to revolve. These clocks are connected by differential gearing with a recording pen carriage *PC*, which is hauled in one direction or the other, according as the brake is lifted from the corresponding clock. The bridge slider moves with this pen, and tends to restore balance. As soon as this is done the galvanometer coil returns to its normal position, the

relay is cut out, the brake springs back, stopping the clock, and the recording pen $P$ comes to rest, until the equilibrium of the circuits is again disturbed. The main difficulty in devising a satisfactory instrument on this general plan has been that of obtaining a delicate and reliable relay. The total current available for operating this is necessarily small, and in such cases the contacts are very liable to stick. This difficulty Professor Callendar has overcome by mounting his contact on one of the arbors of a clock movement $C$. Metallic springs $CF$ press on the contact surfaces, polishing them as they are rotated by the clock. With this arrangement the make-and-break is effected sharply and certainly, in spite of the very small force which is available for pressing the two contacts together. The contact-piece consists of a ring of plantinum $CW$, forming the tyre of a wheel mounted on one of the shafts of the clock. A spring fork connected electrically with one terminal of a voltaic cell, or secondary battery, grips this metallic tyre on either side, and polishes the contact surfaces as they move round. Contact is made by one or other of two pieces of stout platinum or gold foil fixed at the end of the long horizontal rod, which, as shown in Fig. 343, is carried by, and moves with, the coil of the D'Arsonval galvanometer $GC$. This rod carries with it two insulated copper wires $GF$, which are connected at the contact-making end with one or other of the two platinum wires above mentioned. At the other end the wires connect with one or the other of the two magnets $MM$, controlling the clock brakes. These magnets are clearly shown in the figures, mounted above the cases containing the clockwork.

The clockwork consists of two clocks connected with a simple differential gear, so that the screw pulley $PS$, which drives the silk cord $PD$ connected to the pen-slide, is turned in one direction or the other according to the deflection of the relay.

The carriage carrying the recording pen, and also the Wheatstone bridge slider, is coupled at either end with a cord making two complete turns round the hauling spindle, as shown. A spring fastening at each end of the cord keeps its tension properly adjusted. Just below the guide-bar, on which this carriage moves, are the bridge and galvanometer wires over which the slider passes. The two lie in the same horizontal plane, and the slider consists of a platinum silver fork bridging the space between them. The front wire is connected at either end with the battery, whilst at the back is connected to the D'Arsonval galvanometer. The potential along this battery wire of course falls from end to end, and as the slider moves along the potential of the galvanometer wire is raised

or lowered accordingly. A cut-off is arranged at either end of the travel of the pen carriage, which breaks the magnet circuits, and thus prevents the pen overrunning its cylinder. This latter consists of a light drum of very thin brass, to which squared paper can be fixed in the usual way. The spindle carrying this drum is connected by means of toothed gearing to a clock $DC$ fixed to the frame of the instrument.

A recently devised type of mechanism to effect the same object is illustrated in Fig. 344. This is made by the Leeds and Northrup Co.

A governed motor drives both paper and recording mechanism, which operates as follows:

The movements of the galvanometer system 7, which swings about

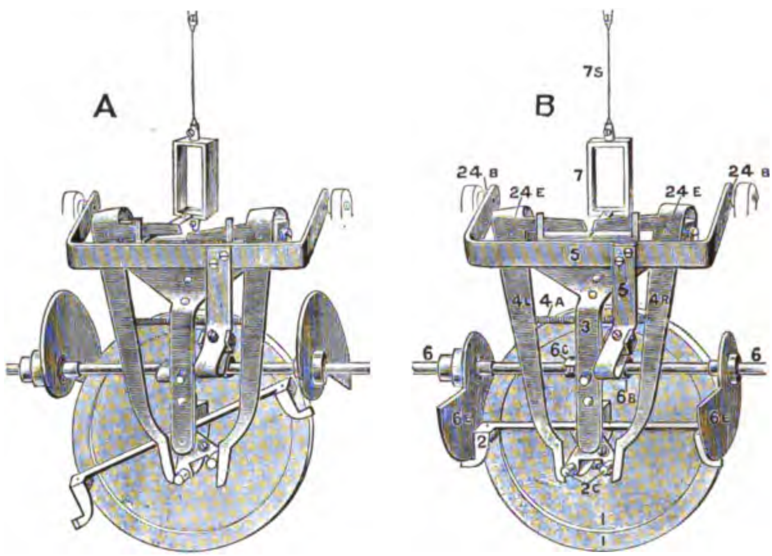



*Fig. 344. — Mechanism of recording potentiometer*

the vertical axis 7 $S$, are controlled by the electrical conditions which are present from time to time in the measuring circuit of the recorder. When the galvanometer system is at its position of rest (i.e. the measuring circuit is balanced), the galvanometer pointer lies directly under the space between the ends of the two right-angle levers 4 $L$ and 4 $R$, which are held pivoted at 24 $E$ and 24 $E$. From this position of rest the galvanometer system may deflect under the influence of current in the galvanometer, until its pointer lies at any position between the stops at the two ends of the rocker arm 5. By the cam 6 $B$ on the motor-driven shaft 6, the rocker arm, which is pivoted at 24 $B$, is periodically raised, and as it is raised, it picks up the end of the galvanometer pointer and

lifts it. If, at that instant, the galvanometer is balanced, the pointer is raised into the space between the two levers 4 *L* and 4 *R*. If, however, as the rocker arm is raised the galvanometer is unbalanced and its pointer lies under one or the other of the right-angle levers 4 *L* and 4 R, which are pivoted at 24 *E* and 24 *E*, the pointer, as it is raised, carries up with it the horizontal side of one of these right-angle levers. A somewhat similar action to the thread recorders already described. The resultant position of the parts of the mechanism due to this movement is shown as a typical case in diagram *A*. The arm 2, which is, as above described, tilted from its horizontal position, shown in *A*, to the position shown in diagram *B*, is one member of a clutch whose other member is the disc 1, and at the instant the above movements took place 1 and 2 were held apart by the cam 6 *C* on the motor-driven shaft. As the rocker arm 5 falls, 1 and 2 come into engagement, and the cams 6 *E* and 6 *E*, rotating, engage with extensions of 2 and restore 2 to its original position, carrying the disc 1 with it. On the same shaft with 1 is the slide resistance of the measuring circuit, and the relationships are such that when movements like the one described above take place, the direction of rotation is such as will tend to restore balance in the measuring circuit. The recording pen (or print wheel) is connected to the disc carrying the slide resistance, and moves with it, so keeping a record of its balance positions.

The amount of rotation given to arm 2 and so to disc 1 depends on the extent of the galvanometer deflection, since the pointer approaches the fulcrum of the lever as the deflection increases. Consequently, the rebalancing movement will be large or small as the unbalance is large or small. In standard instruments the rebalancing steps of the recorder pen vary by uniform gradations from 1/50 in. to 3/4 in., so that large variations may be followed rapidly and small ones accurately. It will be noted that the force of the deflection serves to put the pointer in position and that absolutely no other work is required of the sensitive galvanometer.

## VI. Installation of Pyrometers and Precautions to be Observed

In the preceding pages a brief description has been given of the essential features of various types of pyrometers, and it remains to give a few hints as to the method of installation.

A pyrometer, like every other tool or measuring instrument, will only give reliable results when used intelligently and with due regard to its

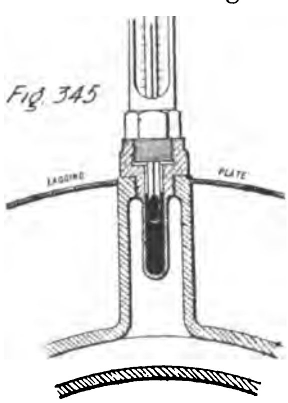
limitations. The same general precautions have to be observed in the installation of mercury thermometers, vapour pressure thermometers, thermocouples and resistance thermometers, so in the subsequent discussion it is to be understood that the remarks apply generally to all the above types.

In the installation of thermometers the fact is frequently overlooked that the temperature indicated by the height of the mercury in the stem is simply and solely that of the mercury in the bulb, and unless the latter approximates very closely to the temperature of the substance which it is desired to measure the readings may be misleading. This obvious fact is often forgotten, as the following examples show.

Take the case of a thermometer fitted in a pocket fixed in a pipe. This pocket can only be in temperature equilibrium with the sample of fluid which comes into direct contact with its walls. Hence it is essential that the pocket should be so fitted that it is fully exposed to the direct flow of the fluid in the pipe. Often, however, the pocket is placed in some out-of-the-way corner where the flow is sluggish and the heat loss from the projecting portions of the fittings high.

The following two practical illustrations of faulty conditions are given by Mr. E. B. Pausey from actual experience :

Fig. 345



Incorrect method of mounting thermometer

(a) *Thermometer Pocket not directly in the Stream.*—The position of the thermometer is shown by the diagram, Fig. 345. The thermometer is supposed to indicate the temperature of the steam at the stop-valve of a steam turbine, and it is therefore a most important item in the calculation of the efficiency of the machine. The pocket is screwed into the upper part of a hollow cylindrical projection cast on the stop-valve body. This arrangement has the apparent object of raising the thermometer to a position clear of the lagging plates on the valve body.

So far from the pocket being fully exposed to the direct flow of the steam a lot of trouble seems to have been taken to place it where there can hardly be any flow at all. Moreover, the radiation losses from the cylindrical projection are bound to be excessive, and, to make matters worse, the bulb of the thermometer only reaches half-way to the bottom of the pocket. The net result is that the thermometer reading is from 80° to 100° F. below the actual steam temperature.

(b) *Thermometer Pocket in a Position where the Fluid is Striated.*—When

the temperature of a liquid flowing in a pipe is required to be measured, it is necessary that the pocket shall not only be exposed to the direct flow, but also that it be not fitted in a place where the liquid is liable to separate into strata of different temperatures ; if no attention is given to this matter, and the fitting is situated in such a place, the natural result will be that the reading of the thermometer will by no means represent the mean temperature of the liquid, but simply that of the stratum in which the pocket happens to be immersed. Fig. 346, which exemplifies a case of this source of error, shows a thermometer pocket as generally fitted to the outlet of an ordinary economiser, for the purpose

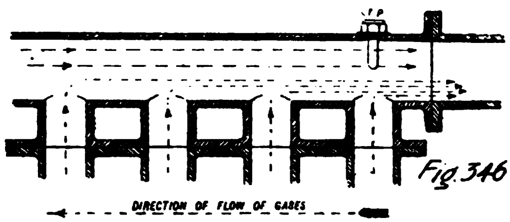
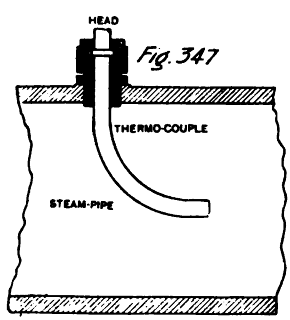


Fig. 346

of indicating the temperature of the feed water supplied to the boilers. From the reading of this thermometer, the probable effect of the economiser in increasing the overall economy of the plant is reckoned. It can be shown that its readings are unreliable, and that any estimates of the efficiency of the economiser based upon them are erroneous and exaggerated—at the same time admitting that the actual usefulness of the economiser is unquestionably so great that it needs no exaggeration, either thermometrical or otherwise.

The thermometer pocket *TP* is shown in its customary position, namely, screwed into the upper main header immediately over the branch leading from the last top box. Now, the temperature of the water issuing from the top boxes is not by any means equal throughout the economiser, but varies in a rather interesting manner, which can be roughly investigated by feeling the branch pipes with the hand. Economisers are generally arranged for the water to enter at the end where the flue gases make their exit, and to leave it at the opposite end where the gases enter, thus, in fact, applying the *contra-flo* principle. If the rough test of the temperatures be started at the water inlet end it will usually be found that the branch at that end is moderately warm, and that at first the temperatures increase as the outlet end is approached ; so far, this is what might be expected from the decrease in the temperature of the flue gases as they pass through the economiser. The maximum will not, however, as one might suppose, be found at the

water outlet end, but is generally somewhere near the middle, the temperature of the branches thereafter falling off more and more rapidly as the water outlet end is approached, until that of the last branch—the one immediately below the thermometer pocket in the illustration—may be but little above that of the inlet water, in spite of the fact that the tubes at this end of the economiser receive heat from the flue gases when the latter are at their hottest. This is due to the flow of water in the economiser tubes not being equal throughout the economiser; it is very much less at the water inlet end than at the outlet end, owing to a large proportion of the water being carried by its own momentum past the branches at the inlet end to those at the outlet end. The natural result of this is a lower temperature rise in the tubes at the outlet end as the consequence of the larger volume of water passing through them. Now, the water in the top main header, owing to its slow rate of flow in the branch pipes, does not become mixed to any great extent; an idea of its behaviour is given by the arrow-headed dotted lines in Fig. 346, which show how the colder water from the tubes at the outlet end flows along the bottom of the header, missing the thermometer pocket altogether. The latter is, therefore, immersed only in the hotter water in the upper part of the header, and thus it gives an utterly fictitious high reading; the error in one case observed ranged from 30° F. to 60° F. When it is remembered that, according to the rough rule of 1 per cent increase of overall economy for each 10° F. increase of feed water temperature, this error represents a non-existent gain of 3 per cent to 6 per cent, its importance needs no further emphasizing. To obtain correct readings, the thermometer should be installed in such a position that it indicates the temperature of the water after it has passed through a mixing chamber or a valve of the globe type.




*Application of Thermocouple to Steam main*

When the temperature of steam in pipes has to be determined by a thermocouple it is advantageous to have a bent thermocouple, as shown in Fig. 347, which permits of a longer length of the stem to be exposed to the stream and hence reduce the cooling of the junction due to conduction along the sheath.

When taking furnace temperatures the couple can often project through the back wall, as shown in Fig. 348, so that its end is close to the object being heated, but this method of fixing has its attendant disadvantages. Consequently the thermocouples are

frequently fixed close to one wall so as not to interfere with the free working space of the furnace.

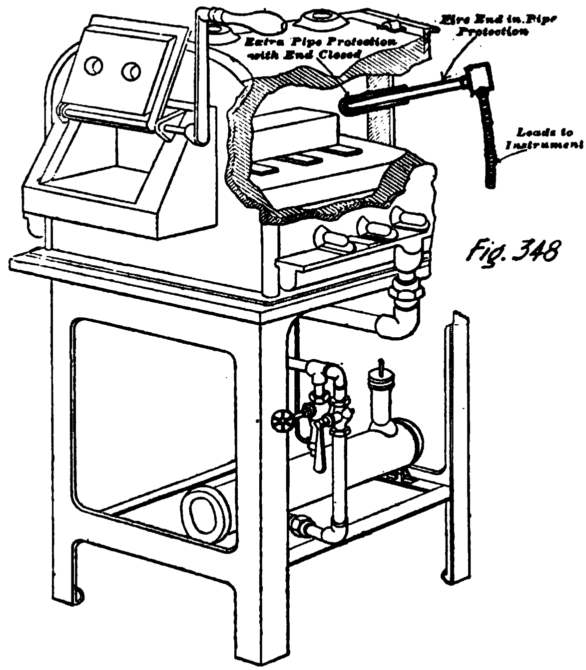



Fig. 348

Radiation pyrometers are generally sighted through the door opening of the furnace on to the object whose temperature is to be determined, but if the furnace atmosphere is smoky or hazy, due to the presence of fumes, this method cannot be used owing to absorption of the radiation by the fumes. In which case the most suitable method is to build into the wall of the furnace a closed end refractory tube and sight the pyrometer on the closed end. It is, of course, necessary to arrange that the portion of the tube projecting into the furnace takes up the temperature of the furnace and that it is not subject to any of the sources of error mentioned above in connection with the installation of thermometers.

## REFERENCES

*Instruments and Methods*

Whipple. "Pyrometry," *Journ. Inst. Mech. Eng.*, Pts. III. and IV. 1913.

Paul. "Electrical Pyrometry," *Trans. English Ceramic Society*, Vol. XIV., Pt. I. 1914–15.

Griffiths. "Methods of Measuring Temperature." Griffin & Co.

Griffiths and Schofield. "Pyrometer Standardisation," *Trans. Fara. Soc.* (1917).

Bash. "Steel Furnace Temperature Measurements," *Iron and Coal Trades Review*, Dec. 26th, 1919.

—— "Testing Pyrometers," *Iron Trades Review*, Jan. 9th, 1919.

Pausey. "Pyrometer Installation," *Electrical Review*, Vol. LXXIX., p. 706. 1916.

Goheen, John P. "Application of Pyrometers to Ceramic Industry," *Bull. Am. Ins. Min. and Met. Eng.*, Sept., 1919.

Griffiths, E. H. *Nature*, 53, p. 39. 1896.

*Temperature of Cylinder Walls and Pipes*

Donkin, Bryan. "Temperature of Cylinder Walls," *Proc. Inst. Civil Eng.*, Vol. M., 1889–94; *Proc. Inst. Mech. Eng.*, 1893–1895.

Coker and Scoble. "Cyclical Changes of Temperature in a Gas Engine Cylinder." *Minutes of the Proceedings of the Inst. of Civil Eng.*, Dec. 16th, 1913.

Callendar and Nicholson. "Steam Temperatures," *Proc. Inst. C.E.*, p. 131 (1898); *B.A. Reports*, p. 422 (1897).

Callendar and Dalby. "Gas Engine Temperatures," *Engineering*, 84, p. 887 (1907); *Proc. Royal Soc.*, 80, p. 57 (1907).

Burstall. "Measurement Cyclically Varying Temperatures," *Phil. Mag.*, 40, p. 282. 1895.

Jordan. "Temperature of Pipe," *Proc. Inst. Mech. Eng.*, p. 1317. 1909.

Hopkinson. *Proc. Inst. Civil Eng.*, Pt. II., 1908–9.

Coker. *B.A.*, Section G., 1908–1910.

*Resistance and Thermo-electric Pyrometers*

Foote, Paul D., Harrison, T. R., and Fairchild, C. O. "Thermo-electric Pyrometry," *Bull. Am. Ins. Min. and Met. Eng.*, Sept., 1919.

Foote. "Cold Junction Correction," *Met. Chem. Eng.*, Vol. XI., p. 329. 1913.

Callendar. "Recording Pyrometer," *Engineering*, Vol. LXVII., p. 675. 1899.

Whipple. "Indicator," *Lond. Phys. Soc.*, Vol. XVIII., p. 235. 1902.

Harris. "Deflectional Resistance Thermometer," *Electrician*, Vol. LXII., p. 430. 1908.

Le Chatelier. *C.R.*, Vol. CII., p. 819. 1886.

Woodward and Harrison. "Notes on Couples of Nichrome Constantan," *Met. and Chem. Eng.*, p. 647. 1917.

*Total Radiation and Optical Pyrometers*

Burgess and Foote. "Characteristics of Radiation Pyrometers," *Bull. Bur.*

Coblentz. "Coefficient Total Radiation," *Bull. Bur. Stds.*, Vol. IX., p. 283 (1913); Vol. XII., p. 91 (1915), p. 533 (1916); *Proc. Nat. Acad. Science*, Vol. III., p. 504 (1917).

Burgess and Wartenberg. *Bull. Bur. Stds.*, Vol. X., p. 3 (1914); *Jour. Amer. Chem. Soc.*, Vol. XXVIII., p. 921 (1906).

Forsythe. "A Morse Optical Pyrometer adapted to a Wide Range of Laboratory Uses," *Astrophys. Jour.*, Vol. LXIII., p. 295. 1916.

Forsythe, W. E. "Theory and Accuracy in Optical Pyrometry with Particular Reference to the Disappearing Filament Type," *Bull. Amer. Ins. Min. and Met. Eng.*, Sept., 1919.

Holborn and Kurlbaum. *Ann. d'Phys.*, Vol. X., p. 225. 1902.

Kanolt. "Standardisation by Transition Points," *Bur. Stds.* Tech. Paper No. 10.

Kanolt. *Bull. Bur. Stds.*, Vol. X., p. 295 (1914); Tech. Paper No. 10 (1912).

Wanner. "Optical Pyrometer Polarising Type," *Phys. Zeits.*, Vol. I., p. 226 (1900); Vol. III., p. 112 (1902).

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